A Study on the Reduction of Uncertainty in the Measurement of Power Tool Vibration

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To increase accurateness and reliability of the evaluation of power tool vibration transmitted to an operator, it is necessary to measure the grip and feed forces during the measurement of hand-transmitted vibration. In the study a system was invented to measure the vibration and the grip and/or feed force, which consists of a measurement handle and a PC with a data acquisition system and the corresponding software. Strain gages and an accelerometer were mounted on the handle surface for the simultaneous measurement of the forces and the vibration. The program in the system makes it possible to monitor the grip and feed force during the tool operation so that the operator keeps the applying forces within the pre-determined range. Investigating the vibration total values, frequency-weighted root-mean-square accelerations at the handle, obtained in repetition for each power tool with control of the grip and feed force showed more consistency than those measured without force control. By using the system the experimenter can reduce uncertainty in measurement of hand-held power tool vibration.

Key Words : Uncertainty in Measurement, Power Tool Vibration, Hand-arm Vibration, Frequency-weighting, Applied Force, Grip/Feed Force, Vibration Total Value

Nomenclature

A(8) : Daily vibration exposure
a_{hv} : Vibration total value (m/s^2)
a_{hw} : Root-mean-square single-axis acceleration value of the frequency-weighted hand-transmitted vibration (m/s^2)
F_f : Feed force (N)
F_g : Grip force (N)
F_l : Force measure at the lower part (N)
F_u : Force measure at the upper part (N)
T : Total daily duration of exposure to the vibration a_{hv}
T_o : Reference duration of 8 hours
U : Uncertainty in measurement
W_h : Frequency weighting characteristic for hand-transmitted vibration

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1. Introduction

Various power tools that expose operators to vibration are commonly used in diverse industrial activities. Vibration is caused by the forces of rotation and impact in the power tools used in manufacturing factories, quarries, mines, construction sites, forestry and agriculture, and the operators of the tools are exposed to the vibration transmitted to the operators' bodies through their hands and arms.

Exposure to excessive tool vibration may cause disorders in the blood flow in the fingers, neurological disorders, and functional disorders in the hands and arms. In general, peripheral vascular, neurological and musculoskeletal disorders related to exposure to tool vibration are compositely called "hand-arm vibration syndrome" (HAVS) and tool vibration is called "hand-arm vibration" or "hand-transmitted vibration". Neurological or vascular disorders in workers exposed to hand-transmitted vibration may have individual or composite effects (Griffin, 1990). In many countries, vascular disorders and abnormal symptoms in the bones and joints caused by hand-transmitted vibration are regarded and listed as occupational diseases and, if the occurrence of such an occupation disease is confirmed, compensation is provided for workers (BS 6842 : 1987). In addition, regulations are enforced that limit work hours according to the level of tool vibration. With the introduction of the mutual certification system under the World Trade Organization (WTO), we expect that regulations on vibration exposure will be applied more widely in manufacturing workplaces.

In general, the results of measurement in industry are used as the important data in decision making to establish policies and trade between countries, and to control the quality of products. Such decisions are made by considering the reliability of the measured data, and the indicator of reliability must be consistent, quantifiable, and meaningful. An indicator satisfying these conditions is uncertainty, which is defined as : "a parameter associated with the result of measurement that characterizes the dispersion of the value that could reasonably be attributed to the measured".

In 1993, the International Committee on Weights and Measures established the "Guide to the expression of uncertainty in measurement", based on existing error analysis, to standardize terms and expression methods used to express the results of measurement. The guide is the first uniform standard for the expression of uncertainty to secure the reliability of measurement internationally and, according to this guide, a measured value should be expressed together with its uncertainty.

It is increasingly recognized that it is essential to calculate the uncertainty of each measured value to enhance the reliability of measurement. According to Directive 2002/44/EC (2002) and the Health and Safety Executive of the U.K. (2005), if the vibration total value is 2.5 m/s^2, eight hours' work is allowed per day ; but if it is 3.0 m/s^2, the allowable time is reduced to 5.6 hours. That is, a 20% increase in the vibration total value has an enormous effect on industry. However, because hand-transmitted vibration is measured by acceleration transmitted to the operator, individual differences in applied force between operators is a major factor of uncertainty in measuring vibration ; uncertainty caused by applied force is known to exceed 20% of the vibration total value in some cases (Jeung, 1995 ; Kim, 1996). If measurement uncertainty increases, it may confuse employers or workers who have to decide the allowable working hours per day based on the measured hand-transmitted vibration.

The objectives of the present research are to analyze the effect of the variation in the operator's applied force on uncertainty when measuring and evaluating hand-transmitted vibration, to develop a method of reducing the uncertainty, and to prove the validity of the method experimentally.

2. Measurement of Hand-Transmitted Vibration

2.1 Methods of measurement and evaluation of hand-transmitted vibration

The international standard for measurement and evaluation of hand-transmitted vibration is ISO 5349 : 2001. The level of vibration is represented as the root mean square (rms) of the frequency-weighted acceleration expressed in m/s^2. To measure frequency-weighted acceleration, frequency weighting and band-pass filtering (6.31∼1258.9 Hz) must be used. Frequency weighting reflects the assumed importance of different frequencies causing damage to the hand. In most power tools, vibration transmitted to the hand is known to include effects in all the three measurement directions in the basicentric coordinate system, as shown in Figure 1.

Vibration exposure is evaluated based on the sum of all the three axes. This vibration total value (a_{hv}) is calculated as the root-sum-of-squares of the three component values :

$$a_{hv}=\sqrt{a_{hwx}^2+a_{hwy}^2+a_{hwz}^2} \quad (1)$$

where, a_{hwx}, a_{hwy} and a_{hwz} are the rms of frequency-weighted accelerations for axes x, y and z, respectively.

Daily vibration exposure is derived from the vibration total value and the daily exposure hours. To simplify comparison of daily exposure, daily vibration exposure must be expressed as the eight-hour energy equivalent frequency-weighted vibration total value ($a_{hv(eq,8h)}$) as given by Eq. (2). For convenience, $a_{hv(eq,8h)}$ is expressed as $A(8)$:

$$A(8)=a_{hv}\sqrt{\frac{T}{T_o}} \quad (2)$$

where T is the daily working hours exposed to produce the vibration total value, a_{hv}, and T_0 is the standard eight-hour work time. To measure the exposure by field measurement, we need to calculate $A(8)$ and the vibration characteristic of the tool can be represented sufficiently by calculating a_{hv}.

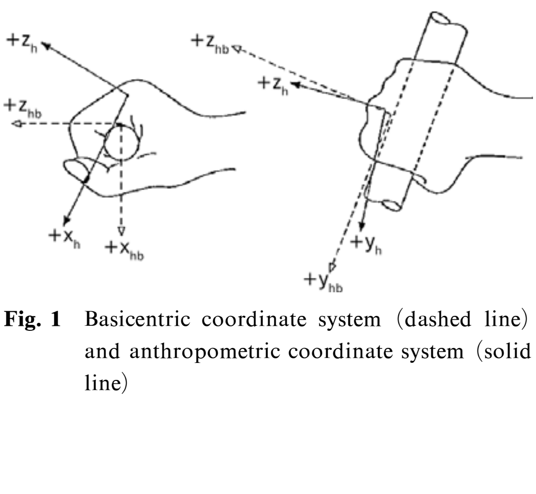


Fig. 1 Basicentric coordinate system (dashed line) and anthropometric coordinate system (solid line)

2.2 Measurement of the applied force to reduce uncertainty

The main causes of uncertainty in measuring the acceleration transmitted to the operator can be divided into those due to the measuring instruments and those due to the working process, as follows.

- Instrumentation accuracy, calibration, electrical interference, mounting of the accelerometers, accelerometer mass and locations.
- Changes from the normal operation of the power tool, changes to hand posture and applied forces, changes in the operator's method of working.

Uncertainty caused by the measuring instrument is usually small compared to that due to the work process. In particular, changes in the worker's posture and applied force make the greatest contribution to the uncertainty of hand-transmitted vibration.

The present study developed a method of limiting the applied force to be within a specific range during measurement to reduce uncertainty in measuring hand-transmitted vibration. For this, we developed a handle to measure and monitor the applied force.

When a worker is gripping a vibrating power tool, the applied force contains a static component and a dynamic component. Because it is important to measure the low-frequency component accurately in measuring the applied force, a strain gage was used as a force transducer. The handle devised to measure the applied force is essentially composed of two cantilevers with semicircular section, as shown in Figure 2. As force is applied, the upper and lower cantilevers are stressed. A strain gage was attached at the root where the strain measured is relatively high, and a Wheatstone bridge circuit and a strain amplifier were used to measure the change in voltage when a force is applied to the handle. The relationship between the applied force and output voltage can be calibrated experimentally.

Figure 3 shows the principle of measuring grip force and feed force when the operator grips the handle and pushes the tool downwards. Grip force is applied to both the top and the bottom, and feed force is applied additionally to the top or the bottom by pushing or pulling. The grip force and feed force cause distributed loads on the surface of the handle, and it is assumed that the distributed load is applied uniformly in the direction normal to the surface. Because only the component in the vertical direction of the distributed load causes the deflection of the top and bottom sections of the handle, the component in the horizontal direction can be excluded. Consequently, grip force and feed force can be expressed separately, as shown on the right of Figure 3. The relationships between the forces measured at the upper and lower (F_u, F_l), grip force (F_g) and feed force (F_f), can be expressed by Eqs. (3) and (4).

$$F_u = F_g + F_f \tag{3}$$

$$F_l = F_g \tag{4}$$

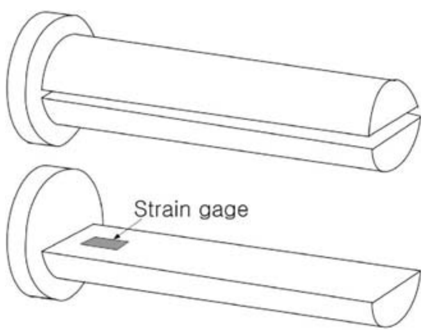


Fig. 2 Handle for force measurement

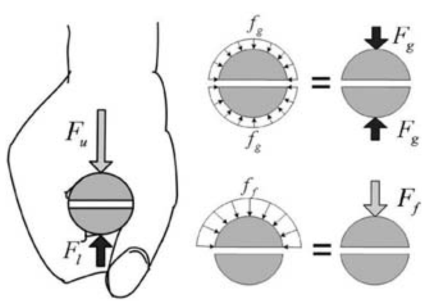


Fig. 3 Grip and feed forces at the handle

F_u and F_l are obtained from the result of experimental calibration of the handle, and by combining Eqs. (3) and (4), we can calculate feed and grip forces. When the handle is gripped and pulled upwards, the feed force is expressed as a negative value.

To monitor the operator's static applied force during the operation of a power tool, first the relation between applied force and output voltage must be determined in the static state. Therefore, we performed a calibration measurement, as shown in Figure 4.

In tool operation, the force applied by the operator is on the whole contact surface ; therefore, we used a flexible artificial leather so that it completely contacted the surface, and the width of the contact surface was Size 7 of BS EN 420 : 1994, which contains regulations on hand size. From the results of the calibration, the relationships between load and output voltage and the sensitivity of the strain gage were derived.

We produced a modified handle to measure the applied force, which is applicable to power tools with an auxiliary handle, as shown in Figure 5.

In this research, we obtained the mean value of strain gage sensitivities from four calibration

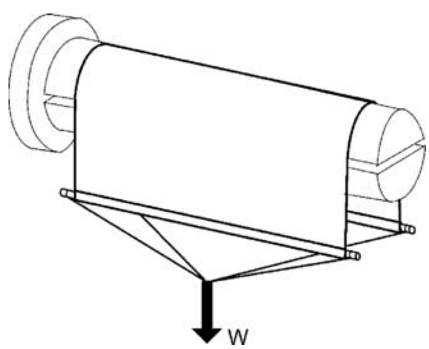


Fig. 4 Determination of voltage sensitivity

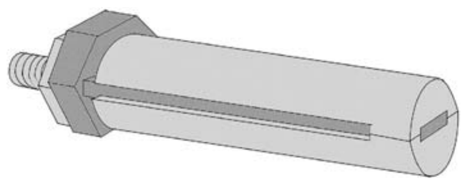


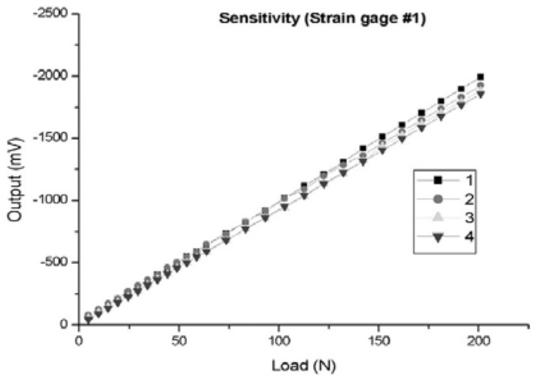
Fig. 5 Handle for force measurement

measurements conducted in the same environment, but on different days.

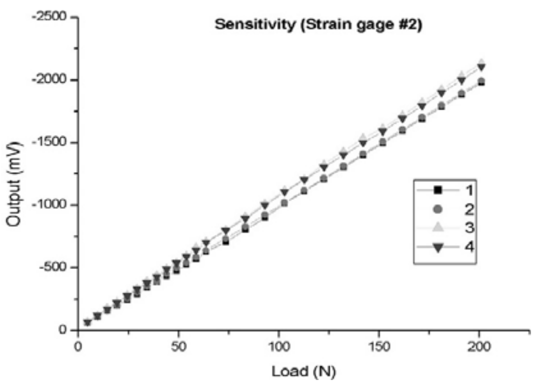
The relationship between output voltage and force obtained for the upper and lower sections is introduced to Eqs. (3) and (4); feed force and grip force are expressed by Eqs. (5) and (6), respectively.

$$F_f[N] = -105.78F_u[V] + 98.F_l[V] \tag{5}$$

$$F_g[N] = -98.19F_l[V] \tag{6}$$



(a) Upper strain gage



(b) Lower strain gage

Fig. 6 Sensitivities of strain gage

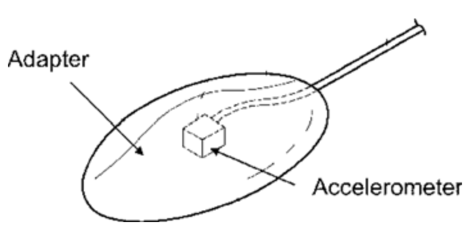


Fig. 7 Adapter for the placement of a 3-axis accelerometer on the handle surface

2.3 Measuring 3-axis vibration

The most accurate method of evaluating hand-transmitted vibration is by measuring the acceleration in three axes between the palm and the surface of the handle. We placed an accelerometer in the palm and inserted it into an adapter made of soft material, as shown in Figure 7, so as not to interrupt the operator's work. To check if the acceleration signals were distorted by the use of the soft material adapter, we attached a vibrator to a cylindrical handle, as shown in Figure 8, and measured the transmissibility between the two acceleration signals while the handle was gripped with a grip force of 30 N and feed force of 50 N. The transmissibility was obtained from the ratio of the accelerations of the accelerometer inserted in the adapter to that of the accelerometer fixed inside the handle. As shown in Figure 9, we found that the transmissibility was maintained at unity without resonance. In addition, the same result was observed with different applied forces (Jang, 2004).

To remove the discomfort resulting from the thickness of the 3-axis accelerometer inserted in the adapter, the thickness should not exceed 10 mm. A commercial subminiature 3-axis accelerometer is expensive compared to a single-axis ac-

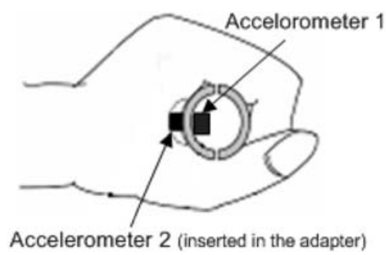


Fig. 8 Placement of accelerometers for measuring transmissibility

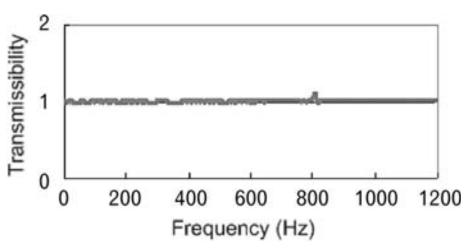


Fig. 9 Transmissibility of the flexible adapter

celerometer, but produces more accurate vibration data.

The present study measured 3-axis accelerations using a subminiature 3-axis accelerometer (8764A500) developed by Kistler, calculated the rms by applying frequency weighting to each component, obtained the vector sum from Eq. (1), and determined the vibration total value.

2.4 Simultaneous measurement system for vibration and applied force

Measuring the vibration total value (acceleration) and the applied force (grip and feed force) simultaneously means that the acceleration is measured while the operator maintains the applied force within a given range. Figure 10 is the schematic diagram of the system that measures the acceleration and applied force of a power tool simultaneously. Figure 11 shows an applied force measurement handle fixed to a 9″ angle grinder, instead of an auxiliary handle.

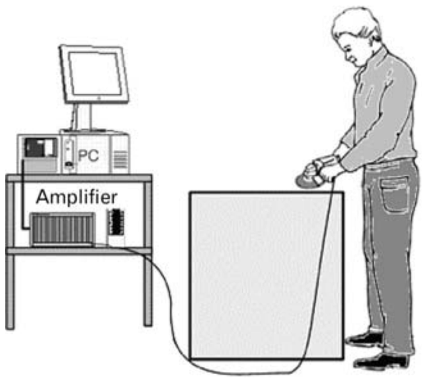
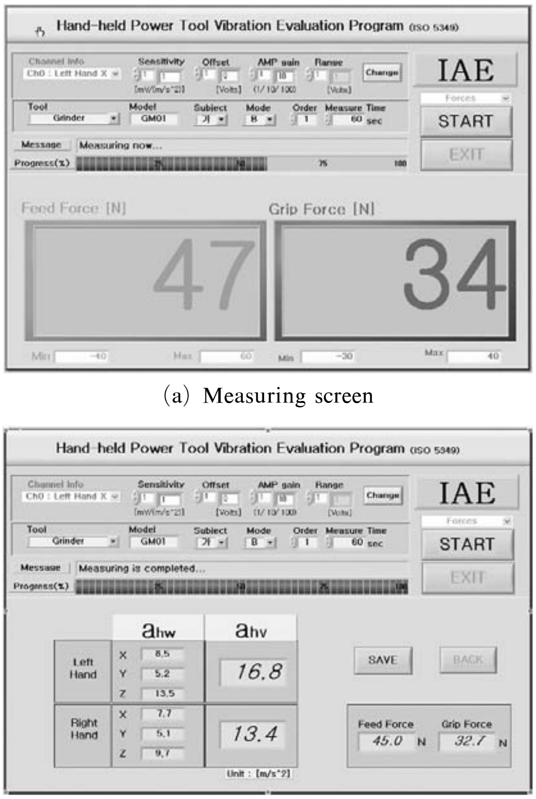


Fig. 10 Experimental arrangement to measure forces and acceleration

Fig. 11 9" angle grinder equipped with a force measurement handle

Figure 11 demonstrates a program developed with LabVIEW to monitor the applied force and evaluate vibration exposure. If the operator tries to monitor the force applied by himself while he is gripping a vibrating power tool, grip force and feed force change constantly and rapidly and are not readable. Therefore, the program was designed to display the value at time intervals of 0.25 seconds. Grip force and feed force for 0.25 seconds were integrated and averaged. Frequency weighting was applied to the measured acceleration, and the frequency-weighted rms value for each axis displayed. Although the applied force was only measured at the handle, acceleration could be measured at both ends or selectively. In this system, acceleration and applied force pass through the amplifier and are stored in the PC with a data acquisition board (National Instruments, DAQ-6062E). The measuring program,



(a) Measuring screen

(b) Result screen

Fig. 12 Program to monitor forces and evaluate vibration exposure installed in the PC, calculates the applied force (grip force and feed force) and displays it every 0.25 seconds, so that the operator can monitor his applied force and adjust it to be within the given range.

As in the example shown in Figure 10, the applied force is measured during tool operation by fixing an applied force measurement handle instead of the auxiliary handle on the power tool, and simultaneously, the vibration total value is measured using a subminiature 3-axis accelerometer. Experimental determination of exposure to hand-transmitted vibration and the vibration exposure of a power tool was conducted 10 times as a preliminary test and 10 times as the main test. The purpose of the preliminary test was to measure force applied by operators in their daily work. The range of applied forces to be used in the main experiment was obtained by measuring the individual worker's applied force in the preliminary test and calculating the arithmetic mean. The force range obtained was indicated on the monitor, as shown in Figure 9, so that operators could keep within the range.

The calculation to determine tool vibration was made for 60 seconds while force was applied. Based on the mean values, ± 10 N was given as the range of feed force, and ± 5 N as the range of grip force. The range of feed force was larger because grip force is less controllable than feed force. Because most operators cannot reach the given range of applied force at the beginning of tool operation, 10 seconds was given as a waiting time for the operator to reach the given range of applied force. If the operator failed to reach the range within the time or stayed out of the range for more than three seconds during measurement, the measuring process was restarted. Each remeasurement was made after the operator had had sufficient rest.

3. Results and Discussion

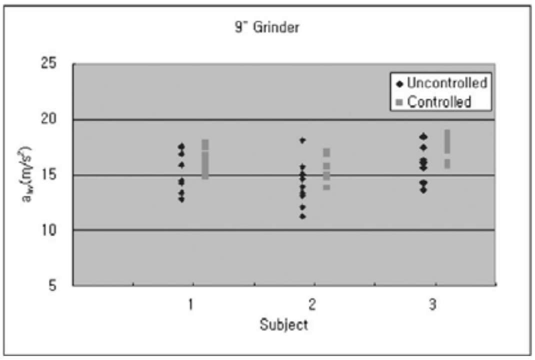
We experimentally analyzed the difference in hand-transmitted vibration between monitoring and maintaining the applied force and not so doing. Figure 13 shows the results of measuring the applied force and acceleration while each of three workers was working with five different tools, and Table 1 shows the arithmetic means and uncertainties in the measured values. $\bar{a}_{hv}$ is the arithmetic mean of the vibration total value, and U is calculated uncertainty based on the "Guide to the expression of uncertainty in measurement" when the significance level was set at 95%; that is, the coverage factor (k) was 2. The coverage factor means a multiple of standard deviation (σ) of the normal distribution.

In an experiment without maintaining the applied force within a limited range, the workers' vibration total value varied so much that it sometimes increased more than three times. However, when the applied force was monitored and controlled, uncertainty was reduced to 50% in the case of the drill. For the two cases, $\bar{a}_{hv}$ sometimes changed by approximately 10%, because the applied force was controlled to be within a specified range based on the mean value of all the operators. The results presented in Table 1 mean that if the applied force is not controlled, it has a significant effect on the vibration measurements and that it is not reasonable to determine hand-transmitted vibration based on the vibration of a power tool measured under different applied force conditions between the operators. Therefore, to enhance the representativeness and reliability of the vibration measurement, it is desirable to measure the hand-transmitted vibration while controlling the applied force to be within a range.

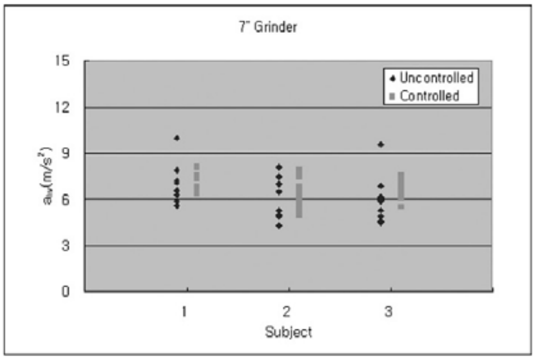
4. Conclusions

The present study devised an applied force measurement handle to reduce the variation of applied force, which is one of the causes of uncertainty that affects the vibration total value indicating hand-transmitted vibration.

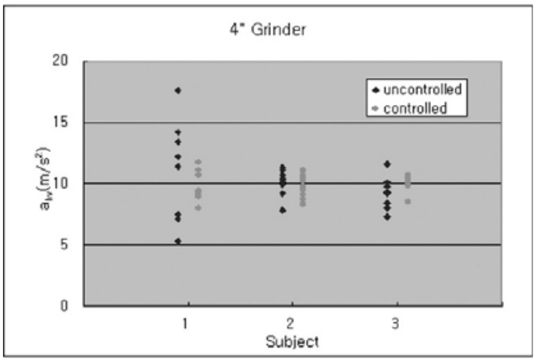
When the applied force was controlled to be within a predetermined range, the uncertainty of vibration total value decreased by up to 50%. Although the devised applied force measurement handle was only usable on power tools with an auxiliary handle, it was concluded that applied force must be measured together with the vibra-



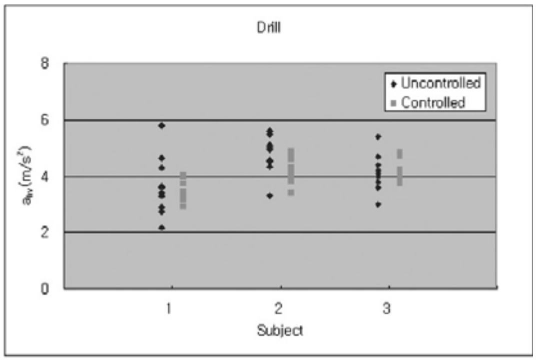
(a) Grinder (A)



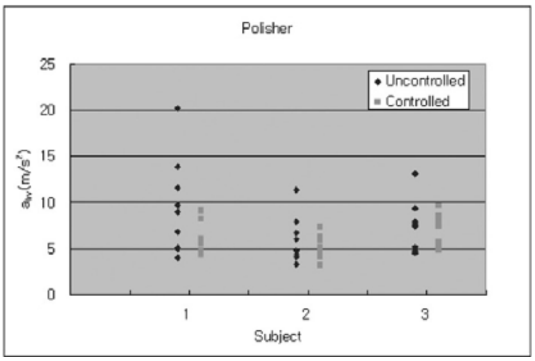
(b) Grinder (B)



(c) Grinder (C)



(d) Drill



(e) Polisher

Fig. 13 Test results of measuring hand-transmitted vibration

Table 1 Test results of measuring hand-transmitted vibration for selected power tools with and without force control

	Uncontrolled		Controlled			
	$\bar{a}_{hv}$ (m/s²)	U (m/s²)	$\bar{a}_{hv}$ (m/s²)	U (m/s²)	F_f [N]	F_g [N]
Grinder (A)	15.3	0.7	16.2	0.5	0±10 N	40±5 N
Grinder (B)	6.4	0.5	6.4	0.3	30±10 N	30±5 N
Grinder (C)	10.0	0.9	9.9	0.4	10±10 N	30±5 N
Drill	4.2	0.4	3.9	0.2	30±10 N	30±5 N
Polisher	7.3	1.5	6.2	0.7	−20±10 N	30±5 N

tion total value to produce reliable data representing the vibration characteristic of power tools.

Furthermore, when exposure to hand-transmitted vibration from a specific tool is measured and the information provided, the representativeness and reliability of the data should be enhanced by providing data of the applied force during the measurement, together with vibration data.

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