University of Cincinnati

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I, Alvin Lim, hereby submit this original work as part of the requirements for the degree of Master of Science in Mechanical Engineering.

It is entitled:
Development of a Semi-Analytic Method to Estimate Forces Between Tool and Hand, Tool and Workpiece in Operation of a Hand-held Power Tool

Student’s name: Alvin Lim

This work and its defense approved by:

Committee chair: J. Kim, Ph.D.
Development of a Semi-Analytic Method to Estimate Forces Between Tool and Hand, Tool and Workpiece in Operation of a Hand-held Power Tool

A thesis submitted to the Graduate School of the University of Cincinnati in partial fulfillment of the requirements for the degree of Master of Science in the Department of Mechanical & Materials Engineering of the College of Engineering & Applied Science

by

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Committee Chair: Dr. Jay Kim
Committee Members: Dr. David Thompson
Dr. Thomas Huston
Abstract

Hand-Arm Vibration Syndrome (HAVS) collectively refers to diseases associated with prolonged, intensive exposure to hand-transmitted vibrations. Millions of construction workers who use hand-held power tools are affected by HAVS in the United States. Numerous dynamic models of the hand-arm system were developed to better understand the injury mechanism. One of the problems in dynamic response analysis of the hand-arm system has been difficulty in finding the excitation forces generated by the operation of hand-held tools. Especially, the force transmitted to the hands from the tool and the force interacting between the tool and work-piece are very useful information in hand-arm vibration study; however, they cannot be measured directly. Methods to estimate these forces are developed in this work by utilizing a hand-arm model, the acceleration measured at the hand, and two measured transfer functions of the tool. Experimental validation procedures of the methods are devised, which show the estimated forces are accurate enough to be used for practical applications. The method developed in this work enables estimation of the force acting between the tool and workpiece in a hand-held power tool in operation for the first time. There are many potential applications of the method developed in this work. For example, the methods can be used to make design changes in the handle bar of a grinder to reduce vibration transmission to the hands, ultimately leading to a lower frequency of HAVS.
Acknowledgements

Foremost, I would like to thank my mentor, advisor, and committee chair, Professor Jay Kim, for his encouragement and his patience on this long journey. Dr. Kim has been persistent with me throughout my course work, research, and in my career path. Despite Dr. Kim’s busy schedule as being Head of the Mechanical and Materials Engineering Department, he was flexible and gracious enough to work with my schedule. I truly value and respect everything Dr. Kim has taught me; I trust that others in the future will be blessed by his wisdom and kindness.

I would like to also thank Edward Zechmann for his key contributions in experimental and analytical support for my thesis. I could not have completed my research without his mentorship. With his expertise on safety analysis and measurement systems, he was able to guide me to finish my research. I was glad to have discussed and contributed to other safety projects that Mr. Zechmann was working on as well. I appreciated my time with Mr. Zechmann in the sound lab and especially enjoyed his unique sense of humor.

Lastly, I would like to thank NIOSH for giving me the emotional, mental, and financial support through the Education and Research Center (ERC) training program for my time at the University of Cincinnati. The community of the NIOSH ERC students is unmatched, and I thoroughly enjoyed the interdisciplinary projects that broadened my knowledge. I particularly enjoyed working on the firefighter research project where my team was able to identify Cardiovascular Risk Factors commonly associated with firefighters. We were able to make an impact by not only reporting, but educating local firefighters about these risk factors to improve their lifestyle. Additionally, the NIOSH fellowship allowed me to give my undivided, focused attention on my course work and research.
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Chapter 1: Introduction

Hand-arm vibration syndrome (HAVS) collectively refers to diseases caused by prolonged exposure to intensive hand-transmitted vibration [1], which has been affecting millions of workers who use hand-held power tools. Numerous studies have been conducted on HAVS, which confirmed the causal relationship between a prolonged exposure to vibration and HAVS [1-4]. However, the precise mechanism of the vibration effect on HAVS is not well understood at present because of the complexity of biodynamic responses and underlying physiology of the hand-arm system. International and national standards have been developed over the years to guide measurement of hand-transmitted vibration and risk assessment of the vibration exposure [5, 6]. These standards recommend vibration exposure limits based on the frequency weighted acceleration levels. The frequency weighting functions used in these standards are derived primarily based on subjective equal sensation contours of the entire hand-arm system [5,7,8]. However, many investigators reported that different frequency weightings are needed to assess the damage potential for different parts of the hand-arm system, especially the fingers, based on experimental and numerical studies [9-11].

Hand-arm models of various degrees of complexity have been developed to study many issues related to hand-arm vibrations. The models include lumped parameter models [12], kinematic models [10,13,14] and continuous models based on the finite element method [15-17]. Each of these models has different strengths and weaknesses. These models can calculate the response of the hand-arm system if the force transmitted to the hand from the tool is given. Kennedy-DeJager [18] devised a method to calculate the force transmitted from the tool to the hand by using a hand-arm model and the acceleration measured at the tool. This hand transmitted force is generated by the interaction force between the tool and work-piece, or the
tool force in short, which cannot be measured directly. Knowing this interaction force will be very useful in many applications, for example design optimization of the tool to minimize the vibration to the hand, and the finite element analysis of the hand-arm system that operating the tool. However, there has been no available method developed to calculate this tool force. The major aim of this paper is to develop and validate a general method to estimate this tool force.

Because the hand-transmitted force is the input force to the hand-arm model, various methods have been developed to measure the force both in laboratory using an instrumented handle [19] and field studies on real tools [20]. The sum of the hand-transmitted force can be calculated from the acceleration measured at the hand using the measured driving point impedance [21]. The hand-transmitted force obviously depends on the tool force; therefore the hand-transmitted force has to be re-estimated for each combination of the tool, work-piece and operator if the tool force is not known.

Knowing the tool force will be very useful in engineering efforts to improve tool designs and HAVS study in general. For example, vibration reduction measures of the tool can be developed based on the quantitative force-response analysis if the tool force is known. Or, variations of the hand-arm responses of multiple operators can be estimated without measuring the response of the hand-arm of the operator while in actual operating conditions. Measurement of the tool force is difficult because obviously no sensors can be installed on the tool-workpiece contact surface. An indirect measurement was conducted by Reynolds and Markle using an experimental setup composed of the mass, spring and damper to measure the force by an impact tool such as a hammer [22]. However the development of a general method to estimate the tool force of any type of hand-held powered tool in actual operating condition has not been reported, which was the main goal of this thesis work.
Chapter 2: A Semi-Analytic Method Developed to Estimate the Force Transmitted to the Hand

Dejager [18] developed a method to calculate the force transmitted to the hand by using a hand-arm model and the measured acceleration at the hand as part of his MS thesis. The method is applied to the hand-arm system that is operating a power grinder, and validated experimentally as a preliminary step to develop the method to calculate the tool force.

2.1 Lumped parameter hand-arm model

Various lumped parameter models have been used to represent dynamic characteristics of the hand-arm system [12-14]. Figure 2.1 illustrates the hand-arm system represented by a three degree-of-freedom (DOF) system, a tool and the work-piece. In the figure, \( F_1 \) is the force transmitted to the hand and \( F_{\text{work}} \) is the interaction force between the tool and the work-piece. For brevity, \( F_1 \) will be referred as the transmitted force and \( F_{\text{work}} \) will be referred as the tool force from here.

The equation of motion of the hand-arm system shown in Figure 2.1 can be described in the frequency domain as follows:
\[
\begin{bmatrix}
B(\omega)
\end{bmatrix}
\begin{bmatrix}
X_1 \\
X_2 \\
X_3
\end{bmatrix} = \begin{bmatrix}
F_1 \\
0 \\
0
\end{bmatrix},
\]

(2.1)

where,

\[
\begin{bmatrix}
B(\omega)
\end{bmatrix} = \begin{bmatrix}
  k_1 - \omega^2 m_1 + j\omega c_1 & -k_1 - j\omega c_1 & 0 \\
  -k_1 - j\omega c_1 & k_1 + k_2 - \omega^2 m_2 + j\omega (c_1 + c_2) & -k_2 - j\omega c_2 \\
  0 & -k_2 - j\omega c_2 & k_2 + k_3 - \omega^2 m_3 + j\omega (c_2 + c_3)
\end{bmatrix},
\]

\(\omega\) is the circular frequency (rad/s), \(k_i, m_i, c_i, i=1,2,3\), are the values of the stiffness, mass and damping of the ith element, \(j = \sqrt{-1}\), and variables in bold upper cases are the complex amplitude of a harmonic quantity.

Figure 2.1. Schematic diagram of the hand-arm model holding a power tool in operation.
Typically, lumped parameter models are developed by choosing mass, stiffness and damping variables so that the impedance at the hand ($m_1$) calculated from the model matches with the measured impedances at the hand, which is also called the driving point impedance.

Table 2.1 shows the values of mass, damping and stiffness parameters of three hand-arm models respectively proposed by Reynolds, Daikoku and the ISO 10068 [12,13]. Each model actually has three ancillary models, one for each of $x$, $y$, and $z$ directions. Figure 2.2 shows the definition of the coordinate system defined by ISO 5349-1 [5], adopted in the models in Table 2.1 and this work. It is noted that a lumped parameter hand-arm model cannot be developed uniquely only from the measured driving point impedance because multiple parameters have to be determined from the single information. More recent models have been developed based on impedances measured at multiple points [19] that enable to uniquely determine all mass, stiffness and damping parameters. Such models can be used to calculate vibration responses at points other than the driving point, at $m_1$ and $m_2$ in a meaningful way. The methods developed in this work use only the driving point impedance; therefore, it is not really dependent on the model as long as the model is developed based on a set of proper driving point impedance data. The model developed by Reynolds is used in this work.
Figure 2.2. Coordinate axes used in the hand-arm system analysis and the grinder used as the tool in this study [5]

<table>
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<tr>
<th></th>
<th>Reynolds 3-DOF</th>
<th>Daikoku 3-DOF</th>
<th>ISO 10068 3-DOF</th>
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<tr>
<td></td>
<td>$X$</td>
<td>$Y$</td>
<td>$Z$</td>
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Table 2.1. Parameter values of three lumped parameter hand-arm system models
Figure 2.3 shows acceleration time histories in $x$, $y$ and $z$ directions measured by a tri-axial accelerometer installed on the handle of the grinder shown in Figure 2.2 in its typical operation. The figure shows that the motion in $x$-direction, the vertical direction, is dominant. Therefore the method in this work is developed for the force and the model in the $x$-direction. Obviously the method can be applied to estimate forces in the other two directions exactly the same way.

Figure 2.3. Acceleration time histories measured at the handle-bar of the grinder
2.2 Calculation of the Hand Transmitted Force

The transmitted force, shown as $F_1$ in Figure 2.1, can be calculated by using the measured acceleration and the hand-arm model. The equation of motion, Eq. (2.1), has three available equations and four variables to find, $X_1$, $X_2$, $X_3$ and $F_1$. Therefore if one of them can be measured, the other three can be calculated. In our case, the displacement $X_1$ is obtained from the acceleration measured at the handle bar, $A_1(\omega)$:

$$X_1 = -\frac{A_1(\omega)}{\omega^2}. \quad (2.2)$$

With this, the displacements of two other masses are:

$$\begin{align*}
\begin{bmatrix}
X_2 \\
X_3
\end{bmatrix} &= -\begin{bmatrix}
B_{22} & B_{23} \\
B_{32} & B_{33}
\end{bmatrix}^{-1}\begin{bmatrix}
B_{21} \\
B_{31}
\end{bmatrix}X_1.
\end{align*} \quad (2.3)$$

$F_1$, the transmitted force is obtained as:

$$F_1 = \left[ -\begin{bmatrix}
B_{12} & B_{13} \\
B_{32} & B_{33}
\end{bmatrix} \begin{bmatrix}
B_{22} & B_{23} \\
B_{32} & B_{33}
\end{bmatrix}^{-1} \begin{bmatrix}
B_{21} \\
B_{31}
\end{bmatrix} + B_{11} \right] X_1 = G(\omega)X_1. \quad (2.4)$$

It is noted that,

$$G(\omega) = \frac{F_1}{X_1} = \frac{F_1}{j\omega X_1} = j\omega Z_\omega(\omega). \quad (2.5)$$

where $Z_\omega(\omega)$ is the driving point impedance. Therefore, $F_1$, the force transmitted to the hand, can be calculated directly from the measured driving point impedance as well, which was done by Dong, Welcome and McDowell [19]. Because a hand-arm model is constructed by matching the driving point impedance calculated from the model with the measured driving point impedance, using a hand-arm model is essentially the same as using measured driving point impedance in calculating the hand transmitted force.
Applying Eq. (2.4) at each frequency, \( F_1 \) is obtained as a function of frequency. The time history of the force, \( f_1(t) \), can be obtained by applying the inverse Fast Fourier Transform (IFFT) to \( F_1 \) calculated by Equation (2.4). Figure 2.4 shows \( f_1(t) \) of the grinder shown in Figure 2.2 obtained by the procedure explained above while the grinder is working with a steel work-piece. It should be noted that the force \( F_1 \) contains only the dynamic force acting on the hand. This does not include the push force and the gripping force.

The calculated dynamic force transmitted to the hand shown in Figure 2.4 has the maximum amplitude of approximately 20 N. The accuracy of this estimated force will be dictated by the accuracy of the measurement as well as the variation of the impedance of the human hand-arm. Considering the anthropometric variation of the hand-arm system, very high accuracy is not really needed for the estimated force. An experimental method is developed in this work to estimate the degree of accuracy of the force calculation.
2.3 Experimental Method to Prove Validity of Using the Hand-Arm Model in Calculation of the Forces

The hand-arm model will also be used in calculating the tool force as it will be explained later. Validity of using the hand-arm model in calculating these forces can be shown experimentally by utilizing the measured motion of the free-running tool. If the tool is running free without being engaged with the work-piece, the unbalance force is the only force existing in the system. If the tool is running while suspended by a very soft bungee cord as shown in Figure 2.5 (a), the relationship between the force and displacement is:
\[ F(\omega) = (k - \omega^2 M) X(\omega) = \left( \frac{\omega^2 M - k}{\omega^2} \right) A(\omega) \approx MA(\omega). \]  

(2.6)

Therefore, the unbalance force can be calculated from the measured acceleration of the tool running free-free suspended.

Figure 2.5. Model of the tool running free of work-piece; (a) while suspended by a very soft bungee cord; (b) while running held by a hand-arm

It is expected that this unbalanced force will not change significantly when the free running tool is held by the hand. In this case the motion of the hand-arm and tool system can be described by the 3-DOF system shown in Figure 2.5 (b). It is noted that the compliance of the tool-hand interface is ignored because the masses of the hand and the tool are lumped into one.
The equation of motion in Eq. (2.1) can be solved after replacing $m_1$ by $m_1 + M_{\text{tool}}$ and by using the force calculated from Eq. (2.6) for $F_1$, which will yield $X_1$. The acceleration $A_1$ can be calculated from $A_1(\omega) = -\frac{X_1(\omega)}{\omega^2}$, and the time history of the acceleration can be obtained by applying the IFFT to $A_1(\omega)$. Comparison of the acceleration time history obtained by this way with the acceleration measured at the handle bar of the tool can be used to estimate the accuracy of the method and to calculate the transmitted force $F_T$.

Figure 2.6 compares the two accelerations, one simulated and the other directly measured for the angle grinder of mass 2.23 kg shown in Figure 2.2. The simulated acceleration time history matches well with the measured time history qualitatively as well as quantitatively. The maximum amplitudes of the two time histories are within 15% from each other, and their frequency characteristics are very similar. Considering the anthropometric variation of the hand-arm and simplification of the model such as neglecting dynamics of the hand-tool interface, the accuracy of the calculated force can be considered fairly good. The simulated acceleration closely represents the magnitude and frequency characteristics of the measured acceleration.
Validity of using the hand-arm model to calculate the forces in the tool and hand-arm system can also be seen by comparing the calculated results obtained by using the three hand-arm models in Table 2.1. Figure 2.7 compares the measured and simulated accelerations of the hand-held angle grinder running free-free obtained by using the three hand-arm models, showing the accelerations in the rms amplitude of 1/3 octave frequency components. All calculated and measured accelerations are quite close to one another, which show the validity of using a hand-arm model to estimate the tool force.
Chapter 3. Development of the Method to Calculate the Interaction Force between the Tool and Workpiece.

3.1 Development of the Method

To calculate the force interacting between the tool and workpiece, which will be referred as the tool force, dynamic characteristics of the tool should be included in the system model. In our work, measured transfer functions obtained by impact hammer tests are used for this
purpose. Figure 3.1 shows the definitions of two transfer functions used in this work, and Figure 3.2 shows the impact hammer test setups.

From the free body diagram of the tool shown in Fig. 2.1, the displacement of the tool is obtained as the linear superposition of the displacements due to the tool force ($F_{\text{work}}$) and the hand-transmitted force $F_1$. Therefore;

$$X_1 = H_{12} F_{\text{work}} + H_{11} (-F_1), \quad (3.1)$$

where, $H_{12}$ and $H_{11}$ are measured transfer functions defined in Figure 3.1 and $F_1$ and $F_{\text{work}}$ are the forces shown in Figure 2.1. Notice that $-F_1$ has to be used in Eq. (3.1) because $F_1$ shown in Figure 2.1 is applied in the opposite direction of the force $F$ used to define $H_{11}$ in Figure 3.1.

From Eq. (3.1), the tool force $F_{\text{work}}$ is obtained as follows.

$$F_{\text{work}} = \frac{1}{H_{12}} (H_{11} F_1 + X_1) = \frac{H_{11} G(\omega) X_1 + X_1}{H_{12}} = \frac{(H_{11} f(\omega Z_0(\omega) + 1)) X_1}{H_{12}}, \quad (3.2)$$

Eq. (3.2) tells that the tool cutting force can be calculated if $X_1$, $H_{12}$, $H_{11}$ and $G(\omega)$ (or $Z_0(\omega)$) are known. $G(\omega)$ can be obtained by solving the equation of the motion of the hand-arm system or from the measured impedance, $X_1$ can be obtained from the acceleration measurement (see Eq. (2.2)), and $H_{12}$ and $H_{11}$ can also be measured by the standard impact hammer test illustrated in Figures 3.1 and 3.2. It is noted that $H_{12}$ and $H_{11}$ have to be measured only once for the given tool. $F_{\text{work}}$ can be calculated at each frequency using Eq. (3.2) to obtain the force as a function of the frequency. By applying the inverse Fourier transform, the time history of the force is obtained.
Figure 3.1. Definition of measured transfer functions

![Diagram showing the definition of measured transfer functions](image)

\[ H_{11} = \frac{X}{F} \]

Figure 3.2. Impact hammer test to measure transfer functions

![Image showing the impact hammer test](image)

\[ H_{12} = \frac{X}{F} \]

Figure 3.2. Impact hammer test to measure transfer functions

(a) TF_{11}  

(b) TF_{12}
Figure 3.3 show the time history of the force obtained for the grinder shown in Figure 2.2 working on a steel work-piece. Figure 3.3 shows that amplitude of the tool cutting force is approximately 100 N, almost five times higher than that of the force transmitted to the hand. In addition to having the effect of measurement errors, it should be noted that this force is dependent on the specific hand-arm, the posture and the grip and push forces of the operator.

Figure 3.3. Time history of the interaction force between tool and work-piece calculated by the procedure developed
3.2 Validation of the Method to Estimate the Tool Force

The tool force can be measured approximately by using the set-up shown in Figure 3.4 and 3.5. As shown in the figures, a large block of steel, 90 kg mass and dimension of 40 cm by 17 cm by 17, is placed on soft foam. The lowest natural frequency of the block was estimated to be 5,500 Hz, and the decaying frequency of the block on the foam when a vertical step force was applied and removed was measured to be about 0.5 Hz. Therefore, the block can be viewed as a free-free suspended rigid body mass in a practical sense. The tool force can be estimated from the measured acceleration of the work-piece because:

\[ f_{\text{work}}(t) \approx M a_m(t) \]  \hspace{1cm} (3.3)

where, \( f_{\text{work}}(t) \) is the cutting force of the tool, \( M \) is the mass of the block and \( a_m(t) \) is the measured acceleration of the block. This setup may be considered as a simplified version of the setup used by Reynolds and Markle [22], which had known mass, spring and damping constants, to measure the tool force of an impact tool.
Initially an unexpected result was obtained from this method, however. Figure 3.6 compares the measured and calculated cutting force, which shows the measured force is far greater than the
calculated force. The highest measured force is nearly 20 kN, which is unrealistically high, indicating existence of measurement artifacts.

Figure 3.6. Initial comparison of the analyzed and measured time histories of the interaction force between tool and work-piece

Figure 3.7 (a) shows the frequency spectrum of the measured acceleration of the block, which shows that very large high frequency components dwarf all low frequency components. These high-frequency components are believed to be due to the elastic waves picked up by the accelerometer, not the acceleration of the rigid body motion. Figure 3.7 (b) shows the frequency spectrum of the measured acceleration after filtering out frequency components higher than 1,500 Hz, which is used to calculate the time domain tool force.
Figure 3.7. Frequency spectrum of measured acceleration of the work-piece of large-mass block.

(a) Unfiltered measured acceleration; (b) Filtered acceleration
Figure 3.8 compares the calculated tool force from Equation (3.2) and the measured tool force converted from the acceleration spectrum in Figure 3.7 (b). The magnitude and frequency contents of the forces are now quite comparable. The maximum amplitudes of the simulated and measured forces are within 30% from each other. Because of approximations involved in the measurement set-up and the hand-arm model, the measured result is not expected to match the calculated data very closely. For example, the transfer functions were measured for a stationary grinder; therefore, the effect of rotation of the grinder wheel is not included. The foam provides the free-free suspended condition only approximately. Therefore, the comparison of the calculated and measured forces serves as an indirect, approximate proof of the calculation method.

![Interaction Force Between Tool and Workpiece](image)

Figure 3.8. Comparison of calculated and measured tool forces of the grinder
Chapter 4. Discussion and Conclusions

4.1 Discussions

The method developed in this work calculates the tool force, the force interacting between the tool and the work-piece (tool force), by using measured transfer functions of the tool and the hand-arm model. This method estimates the tool force, which cannot be measured directly, therefore can provide very useful information for analysis of the hand-arm system. For example, the force can be used to quantitatively estimate the variation of the response of the hand-arm system due to the changes of the dynamics of the tool without conducting new human tests.

One good example of the application of the method can be the design improvement of a power tool to reduce vibration transmission to the hand. For example, a procedure to design a handle bar of the tool that can lower the risk of HAVS can be considered. Eq. (3.2) can be rearranged as follows.

\[ F_1(\omega) = \frac{H_{12}}{H_{11} + \frac{1}{G(\omega)}} F_{\text{work}}, \]  

(4.1)

It is a reasonable assumption that the tool cutting force \( F_{\text{work}} \) does not change by re-design of the handle bar. Therefore, the following procedure can be adopted to design the handle bar.

1. Measure \( X_1 \) of the existing tool while in operation, and calculate \( F_1 \) using Eq. (2.4).

2. Identify desired change of \( F_1 \) by analyzing its frequency components to reduce the frequency weighted vibration input.

3. Design and build a new handle bar that is expected to achieve (2).

4. Measure \( H_{11} \) and \( H_{12} \) of the tool with the newly designed handle bar.
(5) Calculate the new $F_1$ for the given $F_{work}$ from Eq. (3.2)

(6) Check if $F_1$ provides the reduction in the frequency-weighted vibration amplitude. If yes, the handle bar is the final design; if not, go to step (3) for a new iteration.

This procedure can expedite the design process because it does not require new tests for new designs with human operators. The procedure will be able to be used to design of anti-vibration measures for all types of tools.

4.2: Conclusions

In studying hand-arm vibration syndrome caused by portable power tools, the tool force, the force interacting between the tool and work-piece, is important information. However, there has been no general method developed that can measure or estimate this force. A clever method to estimate the tool force was developed in this work that combines a human hand-arm model and experimental measurement. Experimentally, the method is very easy to implement because it only requires one accelerometer at the handle bar of the tool. The method can use either a hand-arm model or the measured driving point impedance (the impedance measured at the hand).

It is ideal if analytical results can be validated experimentally. Experimental validation of the method developed in this work was conducted in two steps. First the use of the hand-arm model in estimating the force was validated by using a free-running powered tool operating hand-held. Then, the overall process of the tool force estimation was validated by comparing the estimated tool force and the measured tool force obtained by using a specially devised experimental setup. These experiments show that the method produces results of acceptable
accuracy for intended applications of the method. Also, this validation shows that mathematics and computer programming involved in the method are correct, especially the use of the fast Fourier transform and the inverse fast Fourier transform that are used to do time-frequency domain simulation.

The method developed in this work enables to estimate the tool force with relatively simple measurements. The force calculated from the methods will be valuable information for further study of hand-arm vibration and HAVS. For example the method enables to study variations of the responses of human hand-arms of various physical sizes without repeating human tests, and more effective design iterations of anti-vibration measures of the portable power tools. Considering the significance of the HAVS and complexity of the problem, numerous experimental, analytical or hybrid methods to study the dynamics of the hand-arm system will be developed in the future. The main contribution of this study, the method that can calculate the tool-workpiece interaction force, will provide basic information for all these methods.
References


