Tuned Mass Damper to Control Hand-Arm Vibrations of Hand-Held Tools

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Abstract

This article concentrates on the problem of hand-arm vibration syndrome that occurs to hand workers who use hand-held tools for digging or drilling. To control vibrations induced in these devices, a tuned mass damper system is suggested here where another handle with elastomeric material is installed around the tools' handle. The new handle is equipped with a passive tuned mass damper used to oppose the dynamic vibrational motion of the tool. This device proved ability to reduce the level of vibrations more than 40 dB (100 times). Simulation results are promising and the device can be installed to any existing tool.

Keywords
Passive damping, Tuned mass damper, Vibration control, Hand-held tool, Finite element.

1. Introduction
Hand-held working rotating machine tools are necessary for most of the hand working processes either indoor or outdoor (see Figure 1). Working on these rotating or reciprocating tools is accompanied with a serious health problem called "Hand-arm vibration syndrome HAVS". This hazard can cause white finger effect caused by narrowing and closing blood vessels when exposing hands to vibrations induced by these rotating machines (Abu Hanieh 2008).

Figure 1. Example of hand-held drilling machine

2. Literature Review

The Medical Research Council performed a survey reported in 1998 that more than five million people were exposed to hand-transmitted vibrations causing Hand Arm Vibration Syndrome (HAVS), were the men's injuries were eight times that of the women (Medical Research Council 1999). Another syndrome caused by vibrations is the Carpal Tunnel Syndrome (CTS) that affect human wrist and hand causing pain, weakness and numbness (Payatakes et al. 2007). These diseases appear mostly in manufacturing and construction sectors where most of the hand working tasks cause vibrations like cutting, cleaning, sewing, finishing and assembly, the common factor of these jobs is repeating the same movement with a hand tool (NIOSH 1985). Thumb, index and middle fingers are the most fingers exposed to this syndrome where they feel of pain, burning and numbness when a tool is dropped or held by hand (Atroshi et al. 1999). Numbness can disappear slowly if cured or stopped working but sometimes syndrome lasts for several months before returning to its normal situation and other times they need special surgery. In severe cases, Carpal Tunnel symptoms do not disappear completely after surgery but stay and the patient suffers for longer times (ElMaraghy and Devereaux 2009).

Mechanical springs and elastomeric pads are used to isolate vibrations from systems, this way is called passive vibration isolation which is considered the easiest and fastest technique of vibration isolation. Passive vibration isolation is called so because it is quite easy and does not need any external power or control systems, it is cheap and can be implemented without any sophisticated technologies (Carella 2008). Active vibration isolation involves several techniques; one of which is the linear active control which is the easiest active technique because it depends mainly on determining the natural frequency and the displacement of the vibrating system (Lamancusa 2002). Nonlinear controllers can serve more applications than linear ones besides that it is more secure because linear ones cause more deflections in severe conditions (Ibrahim 2008). The main objective of vibration isolation is to allow the low frequency disturbances to pass and cut off the high frequency signals (Law et al. 2015). Active vibration isolation isolates high frequency signals in keeping the high frequency attenuation as low as possible, this is done by using sensors and actuators made of semiconductors because they are faster and lower in price (Active Vibration Isolation Systems 2017).

3. Design of Isolation Handle

Vibrations induced on the tip of the drilling tool propagates through the body of the machine reaching the worker's hand. One of the most effective ways to reduce the level of these vibrations is by using a Tuned Mass Damper (TMD). TMD is a passive solution for vibration isolation used to get rid of vibrations at the vicinity of the natural frequency and increasing the attenuation of the response at higher frequencies (Mokrani et al. 2017). The idea of TMD comes from the similarity to the woodpecker bird that uses its beak to dig into trees (Yoon and Park 2011). This woodpecker (shown in Figure 2) is created with a natural TMD in its head where its tongue is connected to the beak by means of hyoid bone circled around the skull as shown in Figure 3. In this case the tongue works as a mass damper when the woodpecker knocks the tree at about 20 times per second with a very high acceleration and deceleration. A spongy bone in the skull serves as the spring damper effect for the TMD (Gibson 2006, Yung et al. 2019).

Figure 2. Woodpecker

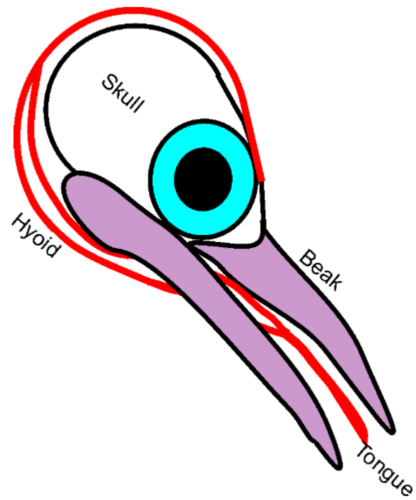

Figure 3. Woodpecker hyoid bone and tongue used as a TMD

Figure 4 shows the Computer Aided Design CAD design for the suggested handle that represents the handling unit and TMD. It consists of an elastomer (rubber) material that has a specific stiffness and damping, the elastomer is surrounded by a 1 mm sheet of metal that serves to give the semi-cylindrical shape of the handle and holds all other parts. Two bolts are used to fasten the handle around the original handle of the drilling machine. This design gives the opportunity to use this mobile handle for any similar machine. TMD here is represented by the small mass mounted to the handle by a flexible leaf spring. The mass and stiffness of this TMD is adjusted according to the natural frequency of the machine tool to place its frequency near that of the machine. The TMD frequency is controlled and adjusted by moving the place of the small mass to increase and reduce the length of the leaf spring changing its stiffness.

The system was modelled using Finite Element Analysis FEA on SOLID WORKS software with tetrahedron elements. Figure 5 shows the von Mises stress results of the static analysis. It is clear that the stress is very low and concentrated on the inner most surface of the elastomer without being spread to the outer surface which gives an advantage to the passive elastomer even before installing the TMD to it. It is quite obvious that adding TMD to the handle will improve significantly the vibration isolation as will be seen in the results section.

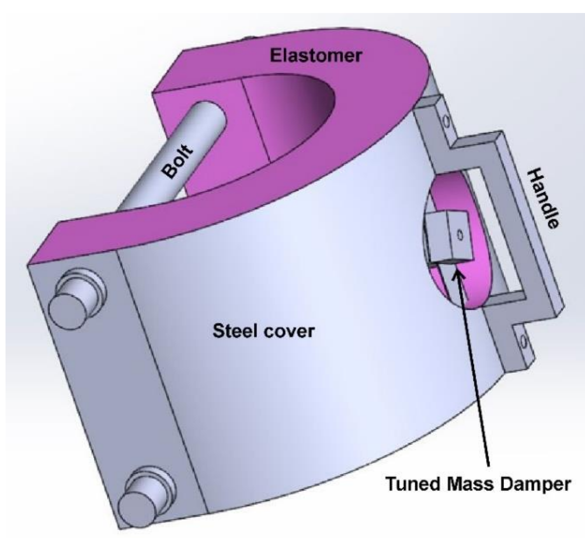

Figure 4. CAD design of Tuned Mass Damper handle

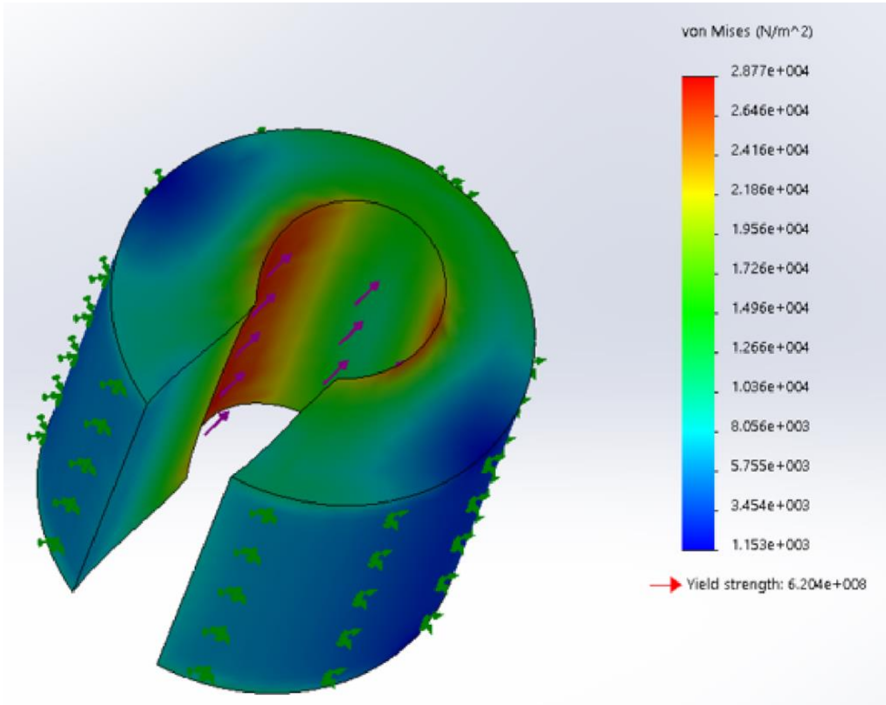

Figure 5. Finite Element Analysis (von Mises stress) of Tuned Mass Damper handle

4. Mathematical Modelling of Handle with TMD

To verify the TMD and the isolation handle mathematically, the free body diagram of the mathematical model is depicted in Figure 6. By analyzing the system shown in this figure;

Where:
F_d: The disturbance force of the drilling machine
x_d: The disturbance displacement of the drilling machine
x_m: The displacement of the isolation handle
x_h: The displacement of the tuned mass
M_m: is the mass of the drilling machine handle
c_m: is the damping coefficient of the machine
k_m: is the stiffness of the machine
M_h is the mass of the TMD
c_h: is the damping coefficient of the TMD
k_h: is the stiffness of the TMD

The second order linear equations of motion governing the system read:

$$M_m\ddot{x}_m = F_d + k_m(x_d - x_m) + c_m(\dot{x}_d - \dot{x}_m) - k_h(x_m - x_h) + c_h(\dot{x}_m - \dot{x}_h)$$

$$M_h\ddot{x}_h = k_h(x_m - x_h) + c_h(\dot{x}_m - \dot{x}_h)$$

To build the state space model for the system, the arbitrary state space vector has been selected to be:

$$e = \{x_d\ \dot{x}_d\ x_m\ \dot{x}_m\ x_h\ \dot{x}_h\}^T$$

The system matrix reads:

$$A = \begin{bmatrix} 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ \frac{k_m}{m_m} & \frac{c_m}{m_m} & -\frac{(k_m + k_h)}{m_m} & -\frac{(c_m + c_h)}{m_m} & \frac{k_h}{m_m} & \frac{c_h}{m_m} \\ 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & \frac{k_h}{m_h} & \frac{c_h}{m_h} & -\frac{k_h}{m_h} & -\frac{c_h}{m_h} \end{bmatrix}$$

Knowing that ($F_d, x_d,\ \ddot{x}_d$) are the inputs representing the force, displacement and acceleration of the drilling machine (source of vibration). The input matrix reads:

$$B = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 0 & 0 \\ \frac{1}{m_m} & \frac{k_m}{m_m} & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}$$

Assume that ($x_m, \ddot{x}_m, x_h, \ddot{x}_h$) are the outputs representing the displacement and acceleration of the handle and the displacement and acceleration of the tuned mass. The output matrix reads:

$$C = \begin{bmatrix} 0 & 0 & 1 & 0 & 0 & 0 \\ \frac{k_m}{m_m} & \frac{c_m}{m_m} & -\frac{(k_m + k_h)}{m_m} & -\frac{(c_m + c_h)}{m_m} & \frac{k_h}{m_m} & \frac{c_h}{m_m} \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & \frac{k_h}{m_h} & \frac{c_h}{m_h} & -\frac{k_h}{m_h} & -\frac{c_h}{m_h} \end{bmatrix}$$

And the feedthrough matrix reads:

$$D = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}$$

These four matrices will help in building the mathematical model and making frequency and time domain analysis as will be seen in the next section.

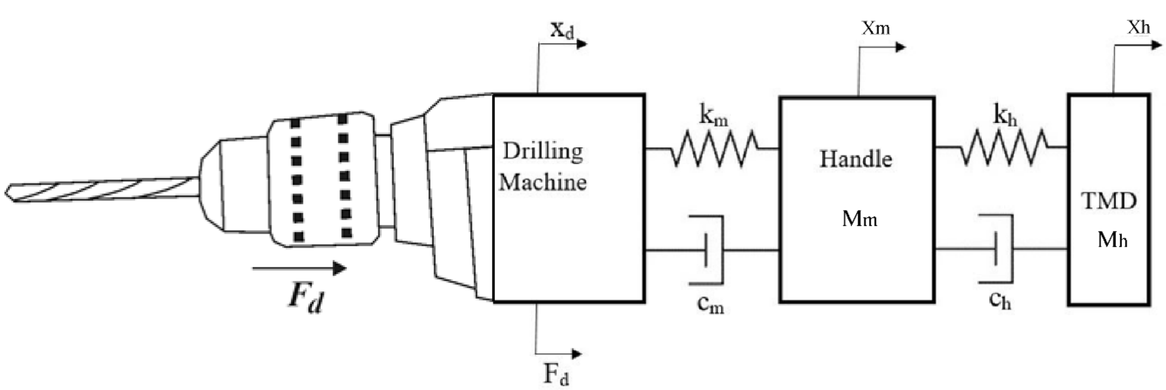

Figure 6. Mathematical model of drilling machine with Tuned Mass Damper handle to reduce vibration effect

5. Simulation Results and Discussion

The foregoing four matrices were inserted to MATLAB software to estimate the frequency and time response of the system. Figure 7 shows the simulation results of the frequency response function (transmissibility) between the acceleration of the drilling machine $\ddot{\boldsymbol{x}}_{\boldsymbol{d}}$ as an input and the acceleration of the handle $\ddot{\boldsymbol{x}}_{\boldsymbol{m}}$ as an output. One can see that the amplitude of the overshoot at the natural frequency (30 rad/s) has been reduced about 60 dB from 80 dB to 20 dB which is quite significant. On the other hand, it is clear that the vibration amplitude at low frequency was not influenced even it has been amplified when approaching near the natural frequency. When looking at the behavior of the system at high frequency, it is obvious that the roll-off of the transfer function at high frequency higher than 45 rad/s increases. This later frequency is called the corner frequency of the system at which the output becomes less than the input for the transmissibility function and it is clear that its roll-off rate has increased from 20 dB/decade to 40 dB/decade and this is caused by the existence of the new mode caused by adding the tuned mass and spring. On the right upper corner for the same figure (Figure 7) the time response of the handle acceleration is depicted showing that without using TMD the oscillations of the tuned mass continue at high amplitude for a long time while using TMD makes the oscillations reach a dead amplitude after about 5 seconds.

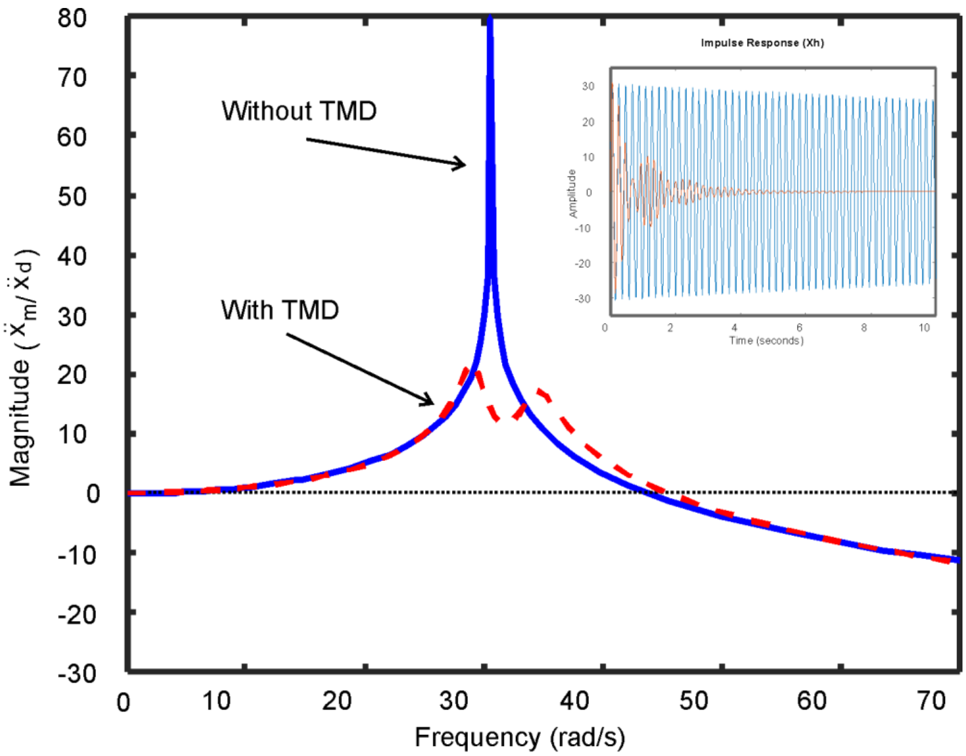

Figure 7. Frequency response function ($\ddot{x}_m/\ddot{x}_d$) and time response

Figure 8 shows a similar simulation for the transmissibility frequency response function between the acceleration of the drilling machine ($\ddot{x}_d$) as an input and the acceleration of the tuned mass ($\ddot{x}_h$) as an output. The overshoot at the natural frequency has been reduced about 40 dB from 80 dB to 40 dB and the roll-off at high frequency also increased from 20 to 40 dB/decade. The time response at the corner shows that the response settles to zero after 7 seconds.

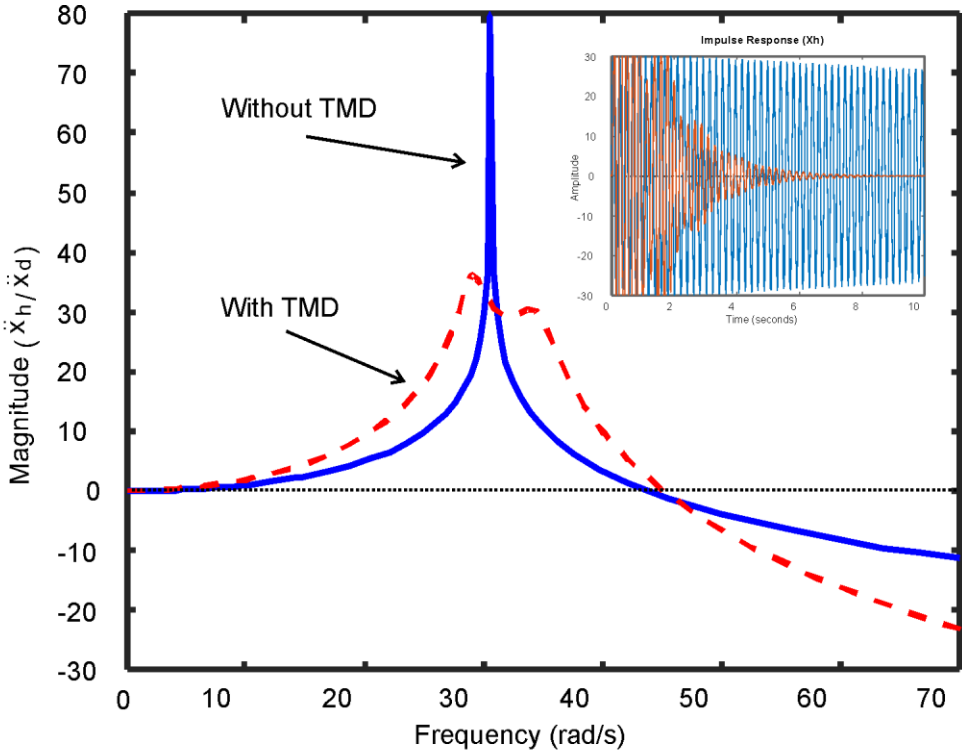

Figure 8. Frequency response function ($\ddot{x}_h/\ddot{x}_d$) and time response

6. Conclusion

This article tackled the problem of Hand-Arm Vibration Syndrome occurs to hand workers when they deal with rotating, drilling or digging hand machines. To decrease the influence of these vibrations on the human body, the idea of Tuned Mass Damper is used here. The idea is based on simulating the way used naturally by the woodpecker where he uses his tongue as a passive tuned mass damper. The tongue is connected to his beak by means of a circular hyoid bone encircling his skull. Similarly, the proposed idea here is to add a mass with a spring and damper to the system. The added mass and spring are tuned to obtain a new natural frequency close to the natural frequency of the system. This cases the mass to move dynamically in a negative direction opposing the motion of the drilling machine. The suggested handle was designed and checked using Finite Element Analysis. The handle is mobile and can be used for a range of machines by just mounting it to the machine handle using its bolts. The performance of the TMD used in this mobile handle has been simulated and verified using MATLAB software. The transmissibility frequency response function showed a very good performance for the damper where it was able to reduce the amplitude of handle by about 40 dB while the amplitude of the tuned mass was decreased by about 60 dB. These are promising results but still they need to be examined experimentally which is recommended to be the next step in this research.

Because of the high importance of this device for the human health, it can be used for any vibrating machine where there is a physical interface with human beings. This can contribute in health and safety of workshops and save lives of hand workers by securing a healthy environment for their daily manual skills.

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Biography

Ahmed Abu Hanieh. Professor in Mechanical Engineering, works in the department of Mechanical and Mechatronics Engineering at Birzeit University - Palestine since 2004 and worked as the department chairman for three years. Participated in more than seventeen research and capacity building projects. Worked on international projects like Tempus projects where one of them aims at establishing a new Master program in sustainable engineering in Birzeit University (ME-Eng) and another Tempus project in the field of modern car maintenance (CODE). Participated in Erasmus Mundus (Avempace II and Avempace III) and Erasmus plus credit mobility projects with different EU universities and Quality Improvement Fund (QIF) projects funded by the International Bank. Established and directed two Master programs (Sustainable Engineering in Production & Renewable Energy Management). Acts as a Palestinian Higher Education Reforms Expert (HERE) since 2015 till now. Supervised two Doctorate students in European Universities. Supervised several Bachelor graduation projects and Master theses. Board member in the Higher Council for Innovation and Excellence in Palestine for six years. Participated in the judgement of several local and international innovation competitions like Made in Palestine, Intel Science competition and First Lego League. Author of three books, more than 22 journal articles and more than 30 conference papers. Volunteer reviewer for more than 17 international specialized journals and conferences. Teaching interests are: Mechanical Vibrations, Fluid Power Control, Dynamics, Measurements and Sustainable Engineering courses.