A Step-by-Step Design of Vibratory Apparatus for Ultrasonic-Assisted Drilling

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Abstract: This paper presents a mechanical design approach, fabrication of a vibratory apparatus which can be applied to vibration assisted drilling (UAD) process. An experimental study was also implemented to validate the ability of the tool holder for twist drill bits in order to superimpose the ultrasonic vibration into the drill bit in UAD. The structure and dimensions of the vibratory components were determined by applying the theory of ultrasonic wave transmission, and then being refined by the modal analysis and practical impedance measurement techniques. The designed and fabricated vibratory unit was then practically checked in drilling. It was found that the device can be effectively used for further experimental studies as well for real production. The design process is depicted step-by-step so that can be easily followed as a practical guideline for similar studies.

Keywords: Ultrasonic Horn, Vibration Assisted Machining, Drilling, Mechanical Design

I. INTRODUCTION

Drilling is a preferable machining process, as it takes about one-third of all manufacturing operations [1]. In addition, dry drilling as well as other dry cutting operations become more preferable as an environmental friendly machining technique. However, this trend would give more challenges in deep drilling of brittle materials [2]. During dry drilling of brittle materials, long and ductile chips tend to bend and coil and thus cause packing of the drill flutes, interferes with chip ejection [3]. At the deeper drilled depth, the increased amount of chips would fill up the flutes, leading to chip-clogging and thus cause the total torque increase exponentially [4-9]. The addition of such chip evacuation torque results in excessive torsional stress, leading to a common failure of the tools known as drill breakage [6, 9, 10]. Whenever the drill broken inside the drilled hole, it is difficult to take out the broken part of the tool from the workpiece, causing catastrophic damage to the parts as well as a considerable economic lost [11].

Ultrasonic assisted machining (UAM) is a technique in which vibrations with small-amplitude, high-frequency is superimposed to the relative motion between cutting tool and workpiece during the machining operation in order to achieve better cutting performance [12]. Several advantages of ultrasonic assisted drilling have been found as to provide significant reduction of thrust force [13-17], improvements in built-up edge [13, 18], burr size [13, 19], tool life and hole oversize (Amini et al., 2013). A significant reduction of drilling torque of 50% when applying UAD for aluminum has been found in the study of Neugebauer and Stoll [20]. The effectiveness of UAD regarding to the reduction of chip evacuation torque, leading to machinabilty improvement in ultrasonic assisted deep drilling of aluminum alloy 6061 has recently been found in several experimental studies of Nguyen and Chu [21-24].

The design of the vibratory unit for clamping the cutting tool for rotary ultrasonic assisted machining is a critical issue. A vibratory unit used in UAD typically consists of a transducer, a horn or sonotrode, the drill bit attached to the horn. Despite abundant studies have been made for designing either the transducer or the horn [25, 26] [27-29], the design steps of the whole vibratory design process has not been presented clearly, making difficult for later investigations for reference.

This paper presents the design approach of a typical vibratory unit with the drilling bit attached to the horn. Each step of the whole design process is depicted in detail. Experimental validation of the cutting improvement when applying ultrasonic vibration onto the drilling process by mean of such designed and fabricated vibratory unit is also presented.

II. DESIGN OF THE VIBRATORY APPARATUS

A. Structure Design

A typical ultrasonic vibratory unit typically consists of three major components: a transducer, a horn and an actuator. The structure of the whole unit for drilling applications can be proposed as shown in Figure 1.

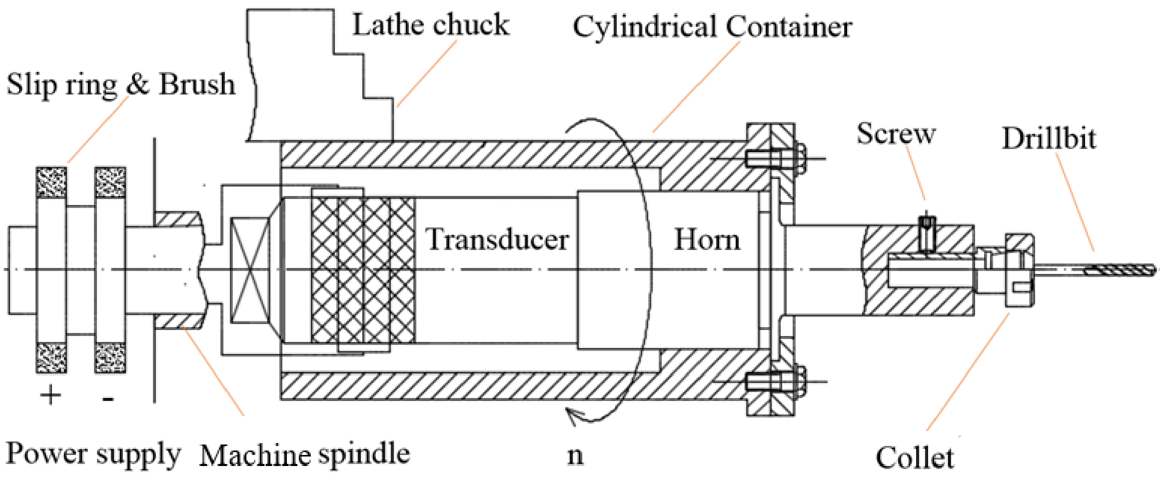

Figure 1. Proposed structure of the vibratory unit

In Figure 1, the vibratory unit is fixed inside the cylindrical container whose clamped in the chuck of the machine. The transducer converts electrical energy, supplied from the power source via a couple of rings and brushes, into proper mechanical vibration. In high-power ultrasonic applications for metal cutting, Langevin transducers are widely used [30, 31]. This kind of transducers is commercially well designed and available for ultrasonic cleaning and welding applications, with a wide range of the power capacity and working frequency. It is cost effective to select a proper commercial transducer. The power capacity of commercial high-power transducers broadly ranges from tens of Watts to several kilowatts. For ultrasonic assisted drilling applications, it has been found that transducers with power capacity from 200 W can be used [16]. The working frequency of a Langevin transducer is actually its resonant frequency, which is carefully checked and provided as the most important value from the manufacturer. In this study, a commercial ultrasonic transducer working with working frequency of 25 kHz was selected. Details of this transducer are depicted in Table 1. The whole vibratory unit then will be carefully designed and fabricated so as to work with such provided frequency at 25 kHz of the chosen transducer for transfer of maximum energy.

Table 1. Selected Ultrasonic Transducer

Contents	Specifications
Model	DW5025-4Z
Frequency (kHz)	25
Ceramic diameter (mm)	50
Ceramic quantity	4
Power (W)	200
Amplitude (μm)	5

The horn, which is sometimes called as the centroid, plays an important role in transmission, concentration and amplification of the ultrasonic vibration from the transducer into the tool. Hence, geometric characteristics of the horn must be carefully determined and validated. It would be worth noting that any changes in dimension of the tool and/or assembly geometry will direct effect on the resonant frequency and thus on the working performance of the whole unit.

The assembly of the horn and the cutting tool would be further scrutinized in detail as shown in Figure 2.

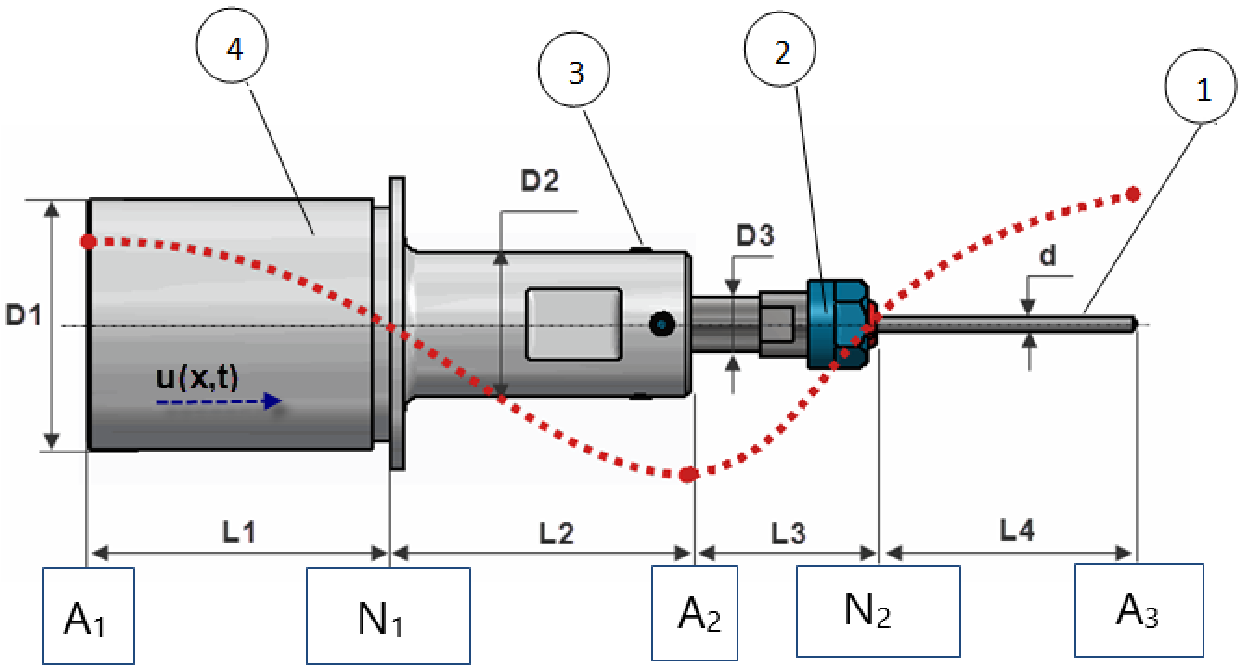

Figure 2. Assembly of the horn and the drill bit

In Figure 2, the tool 1 can be attached to the horn 4 by mean of a collet 2. The collet is fixed inside the horn by screws 3. The longitudinal dimensions L_i (i=1-4) must be computed so as to obtain the maximum amplitude of the vibration at the cutting lips of the tool. The difference in diameter dimensions, D_i is determined based on the vibration amplitude amplification required and the diameter of the the drill bit, d. In this study, a collet ER11, which can be used for dill bits ranged from 1 to 7 mm diameter, was chosen. The detailed calculation process to determine the dimensions of the structure is presented in the next section.

B. Component Design

This design step aims to determine dimension of each components shown in Figure 2 above. Several important parameters of the calculation process are shown in Tanle 2.

Table 2. Propeties of vibratory parts

Part	Metarials	Elasticity E (GPa)	Density (kg/m3)	Sound velocity (m/s)
Horn	Ti-6Al-4V-Grade 5	113.8	4430	5068
Collet	1065 carbon steel (ER11)	200	7850	5048
Drill	HSS (d = 3mm)	207	8300	4994

1) Initial dimensions of the horn dimension

Dimensions of a stepped cylindrical horn can be carried out by using theory with half-wave length principle, which have been well known in several literatures (See for example in [31, 32]. The basic calculation is briefly described as below.

Assigning λ as the length of the ultrasonic wave, c_1 for the sound velocity transmitted in the horn material, ω as the angular frequency; ξ_1 and ξ_2 as the particle displacement at x=0 and at x=L, respectively; E and ρ as the Young's modulus of elasticity and the density of the horn material, respectively; then the lateral displacement, u_x, can be expressed as [33]:

$$\begin{cases} \xi_x = \xi_1 \cos\left(\frac{\omega x}{c}\right)\cos(\omega t) \; for\, 0 \le x \le \lambda/4 \\ \xi_x = \xi_2 \cos\left(\frac{\omega(L-x)}{c}\right)\cos(\omega t) \; for\, \lambda/4 \le x \le \lambda/2 \end{cases} \quad (1)$$

The amplifcation factor for the half-wave, double-cylinder horn is therefore determined as

$$\xi_2 = \xi_1 \frac{S_1}{S_2} \quad (2)$$

where S_1 and S_2 as the cross-sectional area of the horn at x=0 and at x=L, respectively.

For the horn made by Ti-6Al-4V with the characteristic of sound transmission velocity of 5068 m/s (See Table 2), the total length of the horn can be determined as:

$$L_{Horn} = \frac{\lambda_1}{2} = \frac{c_1}{2*f} = \frac{5068}{2*25000} = 101.36mm \quad (3)$$

where f=2πω is the resonant frequency from the transducer.

The location of a special structure used to clamp the horn, called "nodal plane", is the position where particle displacement is zero ($\xi_{node} = 0$) thus can be taken from the following equation:

$$\cos\left(\frac{\omega\xi_{node}}{c_1}\right) = 0 \Leftrightarrow L_1 = L_2 = \frac{L}{2} = 50.7\,mm \tag{4}$$

The next sub-step is to determine the two diameters of the stepped horn. Chosen the small diameter D_2 so as to have enough space for placing the collet body inside. Chosen the gain factor of the horn G, one can then determine the larger diameter of the horn as:

$$D_1 = D_2\sqrt{G}\,(mm) \tag{5}$$

In this study, D_1 and D_2 were selected as 54 and 31 mm, respectively, making the gain factor of 3. Consequently, given the vibration amplitude at the output end of the transducer as 5 micrometers, the amplitude at the end of the horn should be 15 micrometers.

2) Initial lengths of the collet and drill bit assembly

The lengths L3 and L3, corresponding to the free segments of the collet and the drill bit, should be carried out so as the vibration amplitude at the drill tip is maximum (See Figure 2). Applying Equation (1) with the values of sound transmission velocities in the collet and the drill bit are of 5048 m/s and 4994 m/s, respectively, we can get L_3=50 mm and L_4=58 mm.

The initial dimensions obtained will be then used for the final step of the design process.

3) Refined design

The calculated values above are carried out for a horn with two cylindrical steps, without nodal flange dimension and any modified structures required to clamp the collet as well as the drill bit. Such modification in the structure makes change in the frequency resonant of the whole system. It would be noted that, that frequency has to be equal to the original resonant frequency of the selected transducer. Consequently, the whole vibratory unit must be refined using Finite Element Analysis (FEA) technique, until the desired results are achieved. At first, a 3D model of the whole unit, including the horn, the screws, the collet and the tool is built and then import into a Computer Assisted Engineering (CAE) environment which supports FEA. Several available CAE software can be employed, such as ANSYS, Abaqus. In this study, ANSYS R15 was adopted. Modal analysis technique can be applied to check with how changes in the mechanical structure effect on the resonant frequency. To increase the resonant frequency, shortening the total length of the horn was made. In case of reducing the resonant frequency, the length of the segment of the horn with bigger diameter should be shortened . Figure 3 shows the final results obtained. As the resonant frequency obtained at 24959 Hz, very close to the resonant frequency of the transducer, the final dimensions were then used to fabricate the parts.

III. RESONANT FREQUENCY CHECKING

It would be noted that, the fabricating process would have several errors in the part dimensions and forms, as well in the shared lengths between the collet and the horn, the collet and the drill bit, will significantly change the resonant frequency of the whole system.

In order to finally refine the vibratory unit, including the transducer, the horn, the collet and the drilling bit, the resonant frequency must be checked. One of the easiest method can by applied by mean of the total electrical impedance of the whole assembly. In this study, the impedance was measured by the V-I method [34]. A simple measurement circuit is shown in Figure 4.

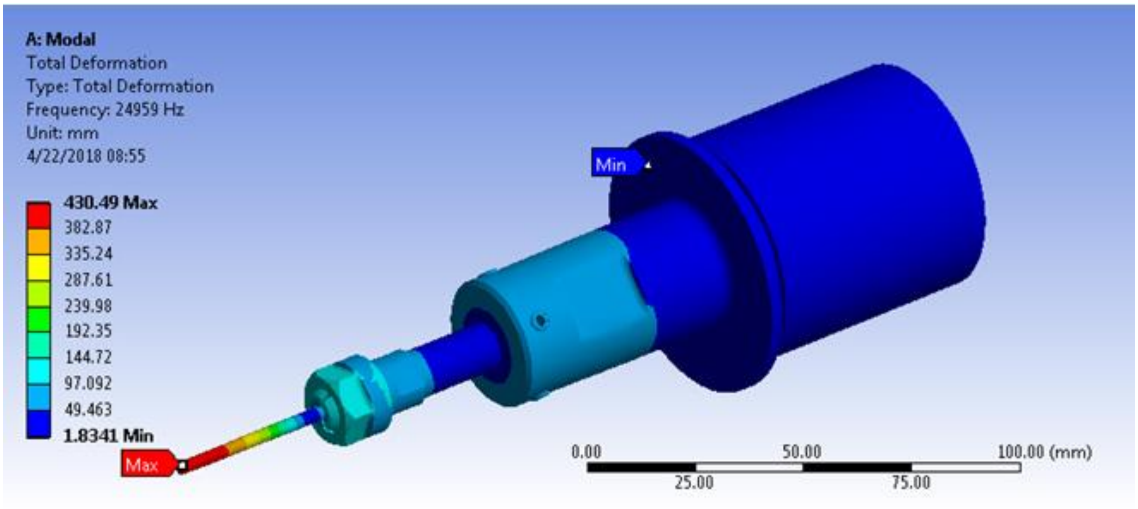

Figure 3. A modal analysis of the horn assembled with the tool bit

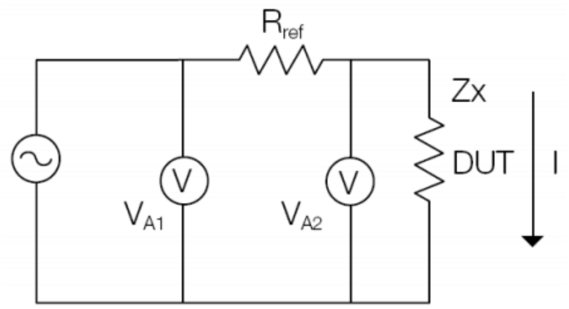

Figure 4. A simple circuit to measure ultrasonic impedance using V-I method

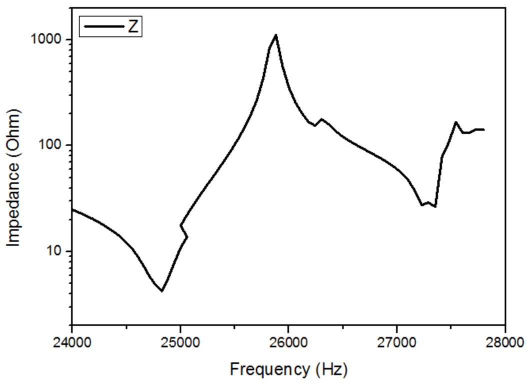

Figure 5. The measured impedance of the whole assembly

A sinusoidal signal with amplitude of 2 V and the swept frequency range from 24000 Hz to 27500 Hz with incremental steps of 50 Hz each was applied to the transducer. Sweeping frequencies and output signal V_{A1}, V_{A2} were implemented by means of corresponding functions of a PicoScope device. The impedance of the ultrasonic actuator can be approximated as:

$$Z_X = \frac{V_{A_2} R_{ref}}{\sqrt{V_{A_1}^2 - 2V_{A_1} V_{A_2} \cos\theta + V_{A_2}^2}} \quad (6)$$

The result obtained is depicted in Figure 5. As can be seen in the Figure, the resonant frequency of the whole actuator is of around 25 kHz, coresponding to the working frequency of the transducer. There are not any resonant frequencies closed to this working frequency, thus make it easy to power up the transducer.

IV. EXPERIMENTAL EVALUATION

A. Experimental setup

A photograph of the experimental setup is shown in Figure 6.

Figure 6. A photo of the experimental setup

In Figure 6, an universal lathe machine (V-Turn 410) was used for implementing the experimental tests. Workpieces were made in the form of square bars with dimensions of 10x10x30 mm3, made from Al6061-T6. The drilling tests were carried out using HSS twist drill bits with a diameter of 3 mm and under dry cutting conditions. The drilling torque was measured by a torque sensor model PCB-2508-03A. A ultrasonic generator model MPI WG-3000 WG was used to convert 50 Hz electrical supply to high-frequency electrical impulses. The frequency range of the generator is 20 to 40 kHz and the frequency step is 1 Hz.

B. Experimental results

In order to check if the vibratory unit can bring about the positive effects on the drilling process, the ultrasonic excitation was swiched off then on after about one second. The output signal from the force sensor, reflecting the changes in the thrust force, was recorded. Figure 6 depicts two examples of the results.

The spindle spped of 1000 rpm and the feeding rate of (a)0.05 mm/rev and (b) 0.085 mm/rev were applied

As can be seen in Figure 7, whenever the ultrasonic vibration is superimposed on the tool bit, the force signal appeared smaller than that without vibration. The significant differences between drilling processes with and without vibration prooved that the fabricated vibratory unit can work effectively.

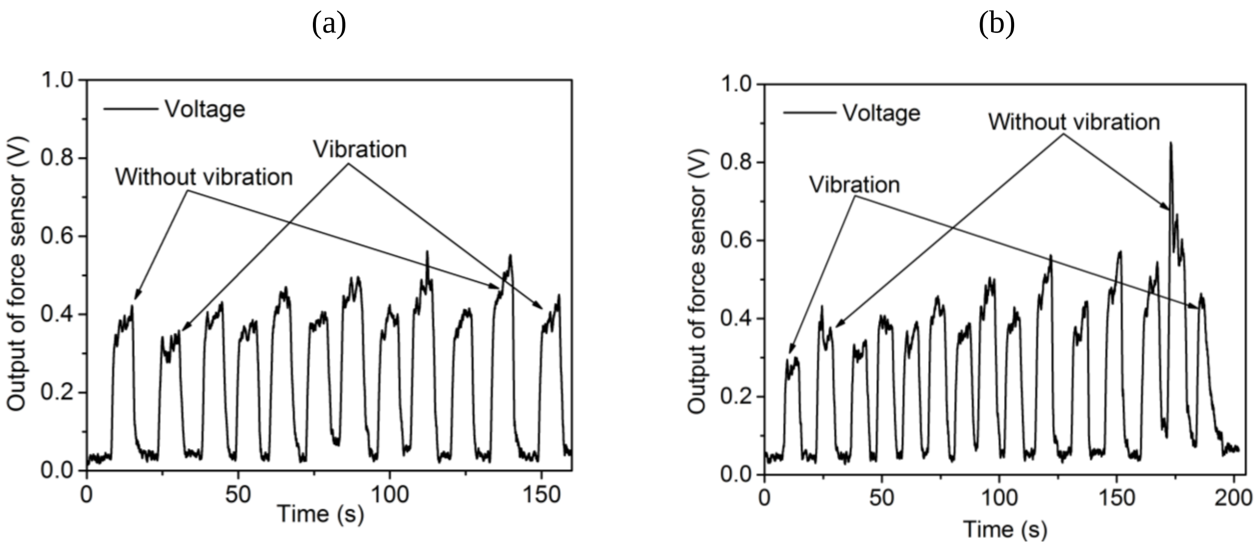

Figure 7. Thrust force signal changes.

V. CONCLUSION

A step-by-step of the design process, refine, checking and experimental validation of an ultrasonic vibratory unit used in assistance of drilling was investigated in this study. The following remarks can be concluded:

- The transducer can be chosen based on the power required and with a certain frequency;
- An initial design step should be done to provisionally determine the segment lengths of the solid ultrasonic horn based on the frequency of the transducer;
- After making the detail structure of the horn and other constructions required to attach the cutting tool, finite element analysis should be done to adjust and refine the structure so as the resonant frequency of the whole system approximately equal to that of the transducer;
- The resonant frequency of the assembled unit can be checked by measuring the electrical impedance of the transducer attached to the horn and the tool;
- The resonant frequency of the whole unit can be adjusted by changing the segment lengths of the horn;
- Further study should be done to develop a mathematical model of the relationship between the horn with attachment structures and the resonant frequency of the whole.

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This volume is dedicated to Late Sh. Ram Singh Phanden, father of Dr. Rakesh Kumar Phanden.

