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Design and fabrication of a novel vibrational system for ultrasonic assisted oblique turning process [†]

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Abstract

We designed and fabricated suitable vibrational equipment for ultrasonic assisted oblique turning process to enable researchers to perform experimental tests with the operating conditions closest to common assumptions of cutting mechanics theories. Applying ultrasonic vibrations to the tool cutting edge along tangential direction and in the presence of inclination and tool cutting edge angles necessitates a novel design and fabrication of vibrational horn with special oblique geometry. In this vibrational horn, the natural frequency of longitudinal vibration mode is forced to be in a certain frequency range of the ultrasonic power supply. The novel tool-workpiece assembly was designed using modal analysis to provide the most conformity of cutting geometry and process parameters between theory and practice. Three-dimensional cutting forces were measured experimentally in vibrational oblique turning process carried out by the mentioned horn. The most suitable conditions to profit from ultrasonic vibrations in oblique turning process were determined, and these experimental results were in agreement with modal analysis results.

Keywords: Ultrasonic assisted oblique turning; Oblique vibrational horn; Modal analysis; Cutting forces; Experimental validation

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1. Introduction

Applying ultrasonic vibrations on a cutting tool along the direction of cutting velocity results in a discontinuous chip removal operation and consequently great reduction in cutting forces. Till now, most theoretical and experimental studies have focused on vibrational orthogonal turning, where inclination angle i is zero and tool cutting edge angle K_r is 90º [1-4]. In this type of cutting process, the components of the resultant cutting force are along tangential and axial directions and lie in the normal plane to the tool cutting edge. Thus, the chip removal operation in conventional and vibrational orthogonal turning could be considered as two-dimensional. Fig. 1 shows the turning process in which i and K_r are the inclination angle and tool cutting edge angle, respectively.

In conventional and vibrational semi-orthogonal turning (zero inclination angle and tool cutting edge angle <90°) [5-8], although the resultant cutting force has three non-zero components in tangential, axial and radial directions, both the chip removal operation and resultant cutting force still occur in two dimensions at the same normal plane to the tool cutting edge, so the process could be easily studied as two-dimensional. In the actual turning process (common in industry, namely, oblique turning) with non-zero inclination angle and tool cutting edge angle < 90°, chip removal operation occurs in three-dimensional space, not in a single plane. The simplicity and intelligibility of orthogonal turning is the base of research works in conventional and vibrational metal cutting processes.

Ultrasonic horns are wave transmitter components designed to vibrate frequently in a longitudinal mode at ultrasonic frequencies. The maximum amplitude of vibrations and the uniformity of that at the working surface, normally determines the performance of such mediums. Seah et al. [9] indicated that calculation of the resonant length of the horn using empirical approximations can be costly and time consuming; besides the designed horn may not be tuned carefully with the transducer and generator. They used FEM for modal analysis of the horns or tool holders to find the natural frequencies in various modes. Cardoni et al. [10] presented a numerically designed block horn with a standard slotting configuration. This guaranteed sufficient tuned frequency isolation from nearby modes as well as high amplitude and amplitude uniformity in working frequency, whereupon avoidance from modal participation of non-tuned modes in longitudinal excitation of the horn was achieved. Yang et al. [11] used Four-end network method and FEM to investigate the ‘local resonance’ phenomenon in stepped horns, which is caused by the abrupt change of section area, and correspondingly, high stress concentration. Rani et al. [12] investigated the design require-

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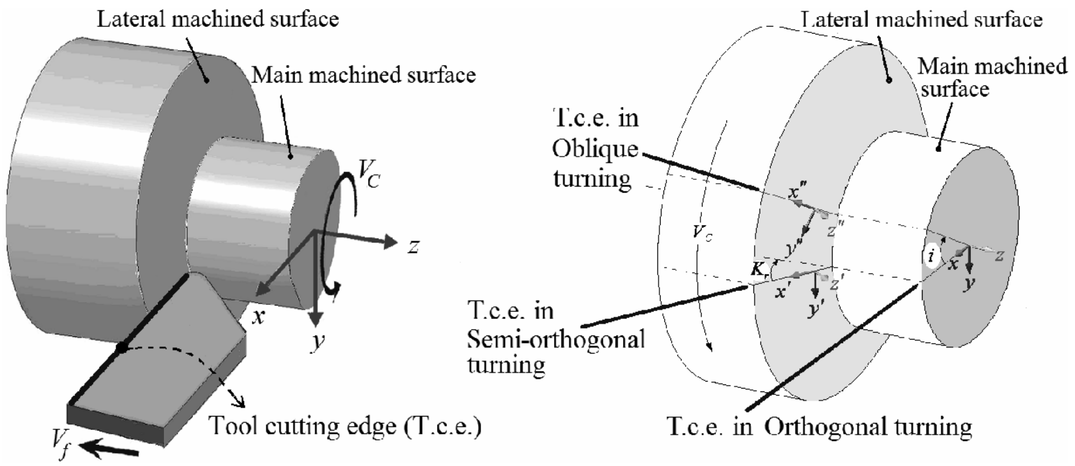


Fig. 1. Orthogonal, semi-orthogonal and blique turning processes.

ments of horns used in ultrasonic welding of thermoplastics. Modal and harmonic analysis was used to assess different horn profiles and configurations in terms of displacement amplitude and von-Mises stresses. Experimental results indicated that welding using Bezier horn shows higher interface temperature and the welded joints had higher strength in comparison with other horn profiles. Rosca et al. [13] proposed a model of axisymmetric ultrasonic horn that has the advantage of a more convenient placement of the nodal point, which is very important in industrial applications. The longitudinal waveform and corresponding horn shape were obtained in two stages: First, it was determined theoretically and with respect to boundary conditions; in the second stage, the experimental setup was designed numerically to give the-required waveform at resonance frequency of the system. Xu [14] investigated the vibrational characteristics of the Cup-shaped ultrasound transducer (CUT), including a sandwich piezoelectric transducer and a cup-shaped horn. By using analytical and numerical methods, they provided the resonance/anti-resonance frequency of the cup-shaped ultrasonic transducer. Results of their research showed that the cup-shaped ultrasonic horn has a good vibrational performance.

Until now several horns and experimental setups have been introduced for vibrational orthogonal turning process, an example of that is the vibrational horn considered by Amini et al. [4], which had only one single insert at the horn tip (due to the symmetry requirements at horns with longitudinal oscillations). In a few other studies related to the vibrational oblique turning process (e.g., Shamoto et al. [15]), ultrasonic vibrations were created by flexural mode-based horns/transducers. Their experimental setup gave ultrasonic vibrations in direction normal to the tool cutting edge, not along the cutting velocity direction, which is a result of the fact that in oblique turning process, the tool cutting edge is not perpendicular to the cutting velocity direction. To improve and develop the previous studies, the design, fabrication and analysis of a suitable experimental setup for vibrational oblique turning process (close to the assumptions of common theoretical oblique turning mechanics model [16-19]), seems quite necessary and is presented in this paper. Besides, previous studies have not provided any clear experimental result regarding horn tip motion to convince that the horn mainly moves in longitudinal direction. The latter issue is also investigated here. To achieve the research's objective, we first assessed and discussed the design and fabrication of an oblique vibrational horn for applying ultrasonic vibrations to the inclined cutting tool in tangential direction (i.e., cutting velocity direction). Next, doing experiments according to most theoretical analyses assumptions requires satisfying the following three conditions: using non-chip breaker inserts, eliminating tool tip radius (to ensure that chip removal is only performed by straight cutting edge), and turning a thin tubular workpiece of minimum thickness and maximum diameter (to reduce workpiece curvature effects, and also reducing the variations of cutting speed along tool cutting edge). It was observed that the developed vibrational system (oblique vibrational horn) necessitates a modified horn end design with two or four mounted inserts (due to the symmetry requirements at horns with longitudinal oscillations). After these steps, we tested the designed horn for its efficiency in delivering ultrasonic vibrations to the cutting zone. The vibration amplitude and cutting forces were measured in the course of horn excitation with different vibration frequencies. It was demonstrated that the horn mainly fluctuates along longitudinal direction. The minimum cutting forces and the maximum vibrations amplitudes were also observed at the resonance frequency. In the end, the performance of experimental setup for ultrasonic vibrations assisted oblique turning process was investigated and verified.

2. Definition of oblique turning

As shown in Fig. 1, three coordinate systems are defined: *xyz* coordinate system, which corresponds to the general coordinate system of CNC lathes; *x'y'z'* or intermediate coordinate system (*xyz* coordinate system rotated by $90-K_r$ degree around *y* axis); and *x''y''z''* or oblique coordinate system (*x'y'z'* coordi-

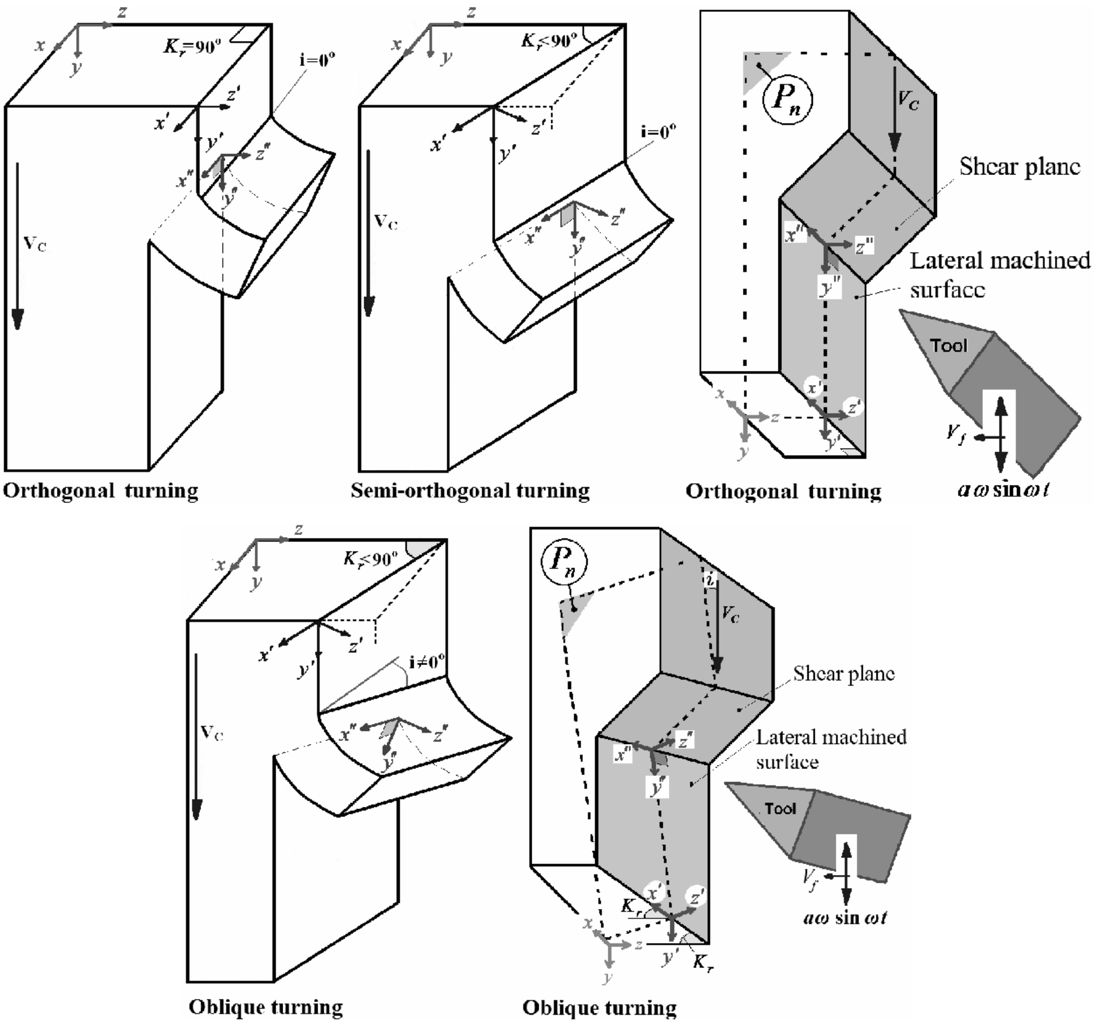


Fig. 2. Orthogonal and oblique 1D-UAT.

nate system rotated by i) wherein x'' is placed on the lateral surface and oriented along the tool's cutting edge; y'' is also placed on the lateral surface and z'' is along direction normal to the lateral surface.

For the purpose of further clarification, a three-dimensional view of orthogonal and oblique 1D-UAT (one-dimensional ultrasonic assisted oblique turning process by the vibrations applied along the cutting velocity) is illustrated in Fig. 2, in comparison with each other. In this figure P_n denotes the plane normal to the tool cutting edge, V_f is the tool feed rate, V_C is the cutting speed, a and f are the vibration amplitude and frequency, respectively; and t is time.

The workpiece velocity in 1D-UAT can be represented in xyz system as follows:

$$\vec{V}_W(t) = \left(V_{X_W}(t),\ V_{Y_W}(t),\ V_{Z_W}(t)\right) = \left(0,\ V_C,\ 0\right). \qquad (1)$$

The cutting tool velocity in 1D-UAT can be written in xyz system as follows:

$$\vec{V}_T(t) = \left(V_{X_T}(t),\ V_{Y_T}(t),\ V_{Z_T}(t)\right) = \left(0,\ a\omega\sin\omega t,\ -V_f\right). \qquad (2)$$

The workpiece velocity relative to the cutting tool in UAT can be obtained as follows:

$$\begin{aligned}\vec{V}_{W/T}(t) &= \left(V_{X_{W/T}}(t),\ V_{Y_{W/T}}(t),\ V_{Z_{W/T}}(t)\right) \\ &= \left(0,\ -a\omega\sin\omega t + V_C,\ V_f\right)\end{aligned}. \qquad (3)$$

where $V_{X_{W/T}}(t)$, $V_{Y_{W/T}}(t)$ and $V_{Z_{W/T}}(t)$ are velocity components along x, y and z directions, respectively. The transformation from xyz system to $x'y'z'$ system is done using a rotation matrix, as follows:

$$\begin{bmatrix} x' \\ y' \\ z' \end{bmatrix} = \begin{bmatrix} \cos(\pi/2 - K_r) & 0 & -\sin(\pi/2 - K_r) \\ 0 & 1 & 0 \\ \sin(\pi/2 - K_r) & 0 & \cos(\pi/2 - K_r) \end{bmatrix} \times \begin{bmatrix} x \\ y \\ z \end{bmatrix}. \qquad (4)$$

Consequently, it can be shown that the workpiece velocity relative to the cutting tool in $x'y'z'$ coordinate system is as follows:

$$\begin{aligned}\vec{V}_{W/T}(t) &= \left(V_{X'_{W/T}}(t),\ V_{Y'_{W/T}}(t),\ V_{Z'_{W/T}}(t)\right) \\ &= \left(-\cos K_r.V_f,\ -a\,\omega\sin\omega t + V_C,\ \sin K_r.V_f\right).\end{aligned} \tag{5}$$

The $x'y'z'$ system is transformed to $x''y''z''$ system as follows:

$$\begin{bmatrix} x'' \\ y'' \\ z'' \end{bmatrix} = \begin{bmatrix} \cos i & -\sin i & 0 \\ \sin i & \cos i & 0 \\ 0 & 0 & 1 \end{bmatrix} \times \begin{bmatrix} x' \\ y' \\ z' \end{bmatrix}. \tag{6}$$

Therefore, the velocity of the material passing through the cutting zone (i.e., workpiece velocity relative to the cutting tool in $x''y''z''$ coordinate system) to undergo vibrational oblique turning will be as follows:

$$\begin{aligned}\vec{V}_{W/T}(t) &= \left(V_{X''_{W/T}}(t), V_{Y''_{W/T}}(t), V_{Z''_{W/T}}(t)\right) \\ &= \begin{pmatrix} a\,\omega\sin i.\sin\omega t - V_C\sin i - \cos i.\cos K_r.V_f, \\ -a\,\omega\cos i.\sin\omega t + V_C.\cos i - \sin i.\cos K_r.V_f, \\ \sin K_r.V_f \end{pmatrix}.\end{aligned} \tag{7}$$

This velocity in vibrational orthogonal turning (at plane P_n), can be written in the following form:

$$\begin{aligned}\vec{V}_{W/T}(t) &= \left(V_{X''_{W/T}}(t), V_{Y''_{W/T}}(t), V_{Z''_{W/T}}(t)\right) \\ &= \left(0, -a\,\omega\sin\omega t + V_C, V_f\right).\end{aligned} \tag{8}$$

These relations demonstrate that although the vibrations are applied along the cutting velocity (both in orthogonal and oblique cutting), for the case of oblique turning, the vibrational movements are not inside the normal plane (to the tool cutting edge) P_n.

3. Vibrational horn design for ultrasonic assisted oblique turning process

The machinability improvement in ultrasonic-assisted turning has a direct link to correct ultrasonic horn design, which must ensure an easy delivery of vibrations to the tool cutting edge and resulting increase in the chip removal rate. An incorrect horn design can make the application of ultrasonic vibrations to the cutting process useless, because regardless of energy consumption, the vibration amplitude in tool tip will be insignificant and all ultrasonic vibrations effects will be eliminated. A precise horn design reduces vibrational energy waste and improves cutting operation.

The first important subject in horn design is the vibrational mode in which horn vibrates [20]. For an ultrasonic vibrational system, there are three fundamental vibrational modes: longitudinal, torsional and flexural. The largest horn diameter should be less than or equal to one-fourth of the vibration wavelength in the corresponding frequency [21, 22]. If this condition does not hold, the effect of lateral vibrations on horn becomes considerable, leading to the waste of energy. For aluminum (E = 71.7 GPa, υ = 0.33 and ρ = 2810 kg/m^3) the largest allowable value is about 64 mm. In addition, the diameter of transducer-attached side of the horn should be greater or equal to the diameter of the transducer. This prevents air from contacting the transducer end; otherwise, at any point when air finds contact with the transducer, all waves will return and acoustic energy will be transformed to heat and will be lost. Because of rough interface between transducer and horn surface and the possibility of air penetration, a connector such as grease, aluminum foil, polymer (for example Mylar) washer, etc. should be placed in their interface to fill the roughness.

It is better to have a horn whose acoustic properties are closer to those of transducer. Horn material should be such that it has the minimum amount of energy loss. For example, since cast iron contains small graphite particles (which absorb sounds), sound transmission in its medium is weak. For horn material, fatigue strength is an important parameter since it vibrates 20000 times per second. All objects have energy loss to some extent, depending on their material. Materials like pure aluminum, magnesium and titanium have a small amount of loss and, therefore, favorable acoustic properties.

From wavelength point of view, there are two types of horn: half-wave and full-wave. In half-wave horns, the length of the horn is half of vibration wavelength and in full-wave horn, it is equal to vibration wavelength. In the present research, we employed the half-wave horn because of its higher stiffness for machining operation, lower (mechanical) energy loss and better clamping options. Recent investigations show that the separation of vibration mode frequencies occurs better in short horns [23].

Also, in horn design, a sudden change in cross section area causes ultrasonic vibrations to return toward transducer, resulting in energy loss (increase in transducer temperature) and subsequently decrease in vibrational speed at horn tip [24]. Therefore, in horn design, sudden change in cross section area should be avoided.

One of the main tasks of the horn (in most processes) is to magnify vibration amplitude. Change in cross section area (from large to small) increases the vibration amplitude. End oscillations in the horns of $n\lambda/2$ length (n is an odd integer) cause $\pi/2$ *Rad* phase change with respect to input vibrations of the horn, i.e., two horn ends are extended and compressed simultaneously.

Among factors influencing the acoustic efficiency of the process, the correct clamping of equipment including transducer, horn and tool plays a fundamental rule. Clamping is done usually at vibrational node position so that vibrations cannot be transferred to clamping system. Anyhow, the transfer of ultrasonic vibrations to the clamping system cannot be completely avoided [21, 22].

A tool can be connected to the horn in two ways: fixed and

Table 1. Mechanical properties of grade 14.9 bolts [25].

Minimum tensile strength R_m	1373 N/mm²
Minimum stress at permanent set limit $R_{0\cdot 2}$ (Yield strength)	1260 N/mm²

separable connections. Fixed connection is problematic, because when the tool is worn out and needs to be changed, the horn must be replaced too. Bolt connection also causes energy loss. In addition, a bolt should have high fatigue strength. Bolts of grade 14.9 are the best in this regard (Table 1):

This grade is known as ultra-high tensile strength fastener. Some mechanical advantages of this grade are as follows:

- Support of highly-loaded joints and therefore more compact designs.
- No risk of failure due to fastener material brittleness.
- No risk of fatigue damage in cyclic loading applications because of high fatigue strength.

Among different bolt grades, bolts of grade 14.9 have the highest values of R_m and $R_{0\cdot 2}$. The higher yield strength in the elastic regime will cause a greater possible elastic strain or a greater possible elastic elongation; e.g., a 14.9 bolt will stretch further than grades 12.9, 10.9 or 8.8 bolts before it yields. However, the bolt of grade 14.9 remains in elastic regime for higher loads and withstands more against fatigue failure when subjected to high frequency cyclic loading. Bolts with square thread or large thread angles must be avoided [24]. To increase fatigue strength in bolt connections, bending loading in bolt should be as small as possible [26]. Therefore, bending mode decreases the fatigue strength of bolt connection between tool and horn.

Based on these design requirements, aluminum 7075 was selected to fabricate the oblique vibrational horn (in Fig. 3). Note that some other materials such as titanium alloys, etc. could be employed for this research work. However, horn is a disposable part and its cost-effectiveness is an important factor for its industrial use, so we focused on Al 7075 as horn material.

In horn design, in order to avoid any lateral vibrations or excitation of bending modes of the horn, four tools (inserts) were symmetrically clamped: two with the inclination angle of 30° and the other two with the inclination angle of 15°.

4. Finite element analysis of designed horn for ultrasonic assisted oblique turning

Modal analysis of a structure must be done to determine its natural frequencies and mode shapes. Modal analysis using finite element involves dividing an object into smaller elements (therefore, fewer degrees of freedom) and solving the governing equations for each element. We used ABAQUS finite element software to perform modal analysis with C3D4 TETRA elements.

During the turning process in the presence of ultrasonic vibrations, one end of the horn is connected to a vibrating transducer and the other end to the cutting tool, while both of them vibrate with maximum possible amplitude. In this state, there are no boundary conditions for both horn ends, making them fixed in a certain position. This implies that the horn should be modeled as free-free part. The clamping operation is done only at vibrational node and since there is no vibration at this point, this issue will not influence the results of finite element analysis [4].

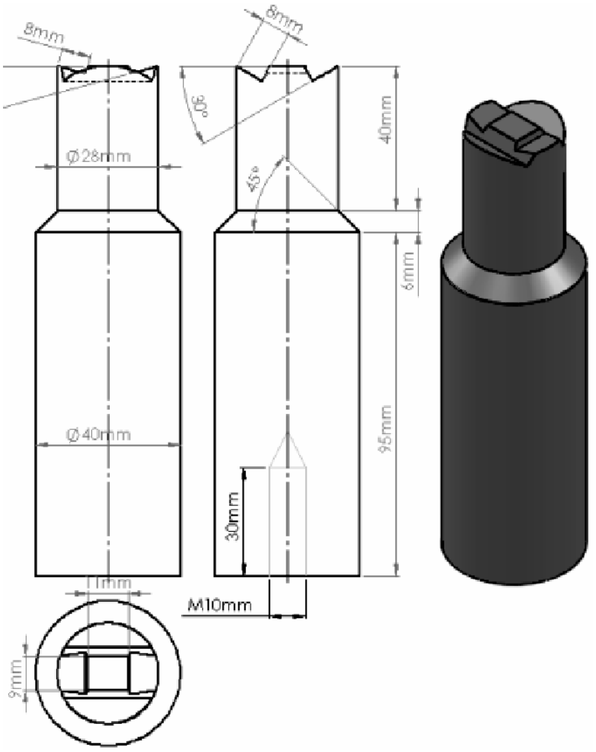


Fig. 3. Designed horn for ultrasonic vibrations assisted oblique turning.

The ultrasonic power supply used in the experiments is capable of producing vibrations in a wide range of frequencies. As a result, designing horn natural frequency in the desired mode does not face any limitations, except that it is better to be higher than the audible range of humans: 20 kHz. Natural frequencies of longitudinal, torsional and flexural modes resulting from modal analysis are shown in Fig. 4.

Upper and lower modes are second torsional and flexural modes, respectively. In vibrational turning, applying ultrasonic vibrations in cutting velocity direction gives the most benefits related to ultrasonic vibrations.

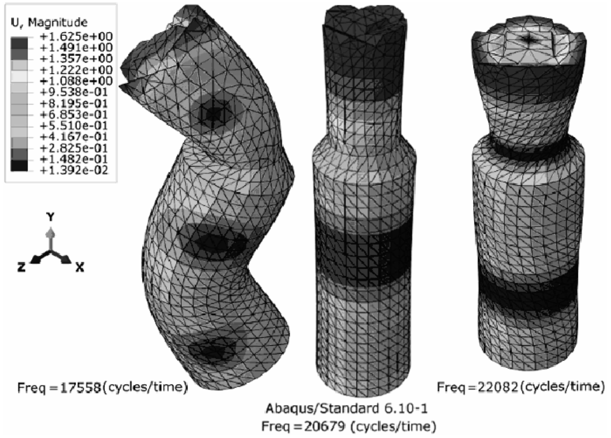
It is expected that when the oblique vibrational horn is excited on its longitudinal mode natural frequency (especially the first mode shape), the optimum condition for oblique chip removal operation can be achieved.

5. Experimental analysis

The aim of this section is to designate and implement appropriate experimental tests with respect to oblique cutting parameters provided by the novel vibrational horn and cutting tool, in order to obtain the best ultrasonic excitation frequency

Table 2. The workpiece properties of tube Al 2024.

Inner diameter	Φ192 mm
Outer diameter	Φ194, 196 mm
Tube thickness	1, 2 mm



Flexural (Second mode)

Longitudinal (First mode)

Torsional (Second mode)

Fig. 4. Horn mode shapes obtained from modal analysis of oblique vibrational horn (in 17-23 kHz range).

in vibrational oblique turning process.

Various types of horns were designed, fabricated and tested. Vibrational node was also determined experimentally through pouring some powder on the horn. Fig. 5 shows some of the fabricated horns with different inclination angles.

To measure the tool vibration amplitude, for the first time a calibrated non-contact measurement eddy current device was used, as shown in Fig. 6.

We used a thin tube of Al 2024 material in experimental tests to eliminate the tool nose radius and carry out chip removal only with the straight edge of cutting tool. The geometrical properties of workpiece are listed in Table 2.

In the turning process, at constant cutting velocity, V_C, any change in workpiece diameter, d, will cause a change in workpiece rotational speed, n, but it does not lead to any change in chip removal rate, so ultimately the only effect will be workpiece cutting with various curvature values. In this research, to overcome the workpiece curvature effects on chip removal operation and reach the ideal chip removal condition (straight chip removing like planning process), it was necessary to select a workpiece with maximum possible diameter. Thus, a tube of 194 mm in diameter was used for the experiments. To minimize the variation of cutting velocity along tool cutting edge, the ratio of tube thickness to its diameter was selected to be as small as possible. Also, to increase the machinability of aluminum thin tube, a Teflon press fitted rod was inserted into the tube. It improved the workpiece dimensional stability during machining process by increasing the workpiece's stiffness. Slot cutting was subsequently performed on definite length intervals on the Teflon rod surface in order to cut only the aluminum tube during right turning tests. The workpiece and experimental setup are shown in Fig. 7.

Fig. 5. Tooling system (horns and inserts) providing obliquity in vibrational oblique turning.

Fig. 6. Eddy current setup (measuring the vibrations amplitude of cutting tool tip).

In accordance with prior research [3, 4, 27, 28], the CNC TM40 turning machine, the Kistler dynamometer 9257B, the ultrasonic power supply and transducer were used to carry out experimental test.

6. Cutting force results

Fig. 8 shows the insert tip motion in *xyz* coordinate system at different forced longitudinal vibrations in the range of 19.7-20.3 kHz.

The data related to angles $i = 15°$ and $i = 30°$ are almost similar, because both of them have been created in one horn. The large amplitude in y direction shows that the horn mainly moves in longitudinal direction. Small-amplitude fluctuations in x and z directions are maybe due to other lateral strains, excitation of mixed modes, or some experimental errors.

Fig. 9 presents cutting forces obtained from three types of oblique horns excited with various longitudinal vibration fre-

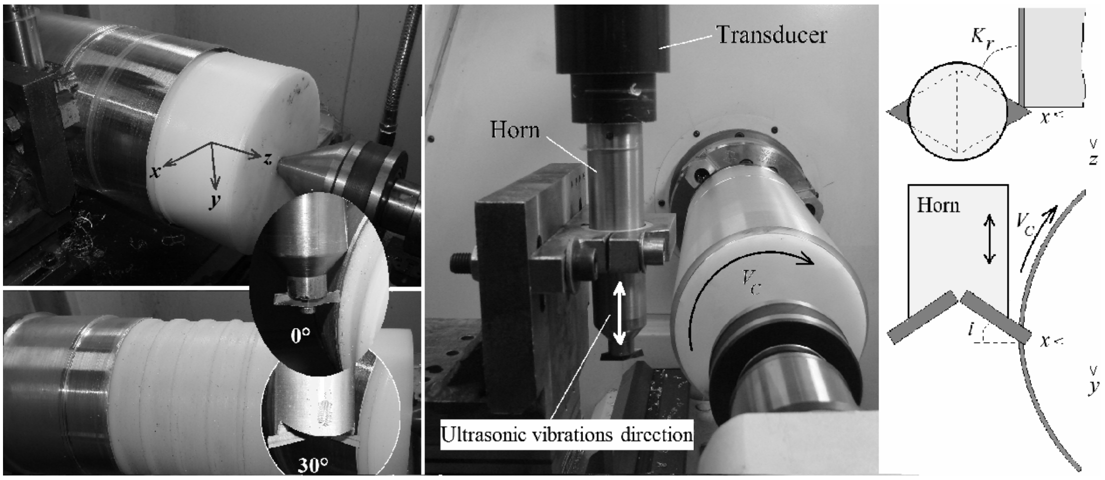
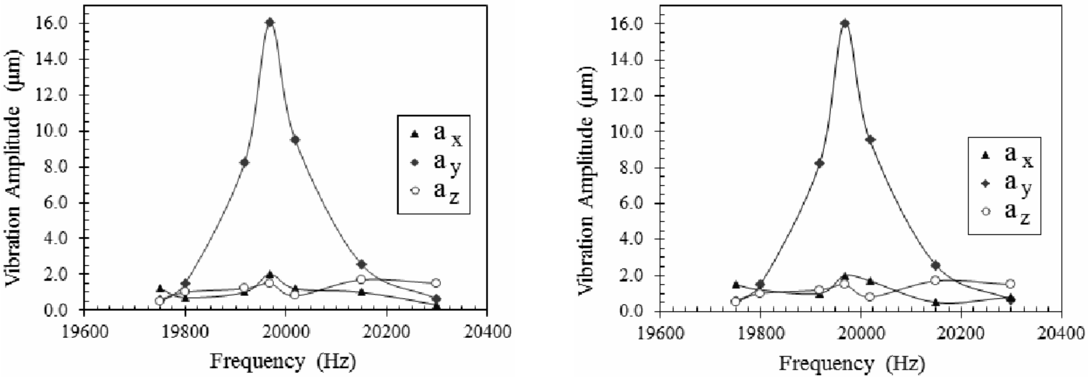


Fig. 7. Experimental setup and workpiece in vibrational turning.



i = 45 deg

i = 15 deg and *i* = 15 deg

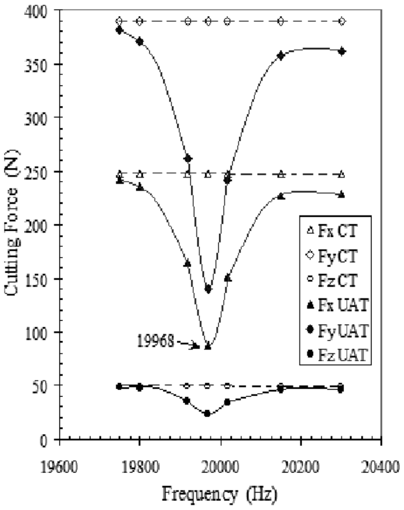
Fig. 8. Changes in vibration amplitude components with respect to excitation frequency of the horn-tool assembly in different inclination angles (tool feed rate of 0.4 mm/rev, cutting velocity of 0.53 m/s and 1 mm depth of cut).

quencies. F_x, F_y and F_z are force components in radial, cutting velocity and axial directions, respectively. The experiments were repeated three times and the averaged data (with negligible scatter) were reported for the following cutting forces. In longitudinal excitation of these horns, the vibrations will be effective for external usages only when the excitation frequency is near the Natural frequency of longitudinal mode (NFLM). As the frequency of applied ultrasonic vibrations gets further away from resonance frequency (NFLM of the horn), this effect drops significantly, approaching the forces of the conventional oblique turning process. Finally, it could be concluded that the most reduction in cutting forces (indicating the most effectiveness of ultrasonic vibrations) occurs in vibrational oblique turning process when the longitudinal excitation of the horn would be done at its NFLM, which is in good agreement with FE analysis results (Fig. 4). To have different inclination angles, different sizes of insert tools should be employed. In this case, using larger and heavier insert tools will be accompanied by an increase in inclination angle. However, Fig. 9 shows that as inclination angle increases, the effective frequency decreases.

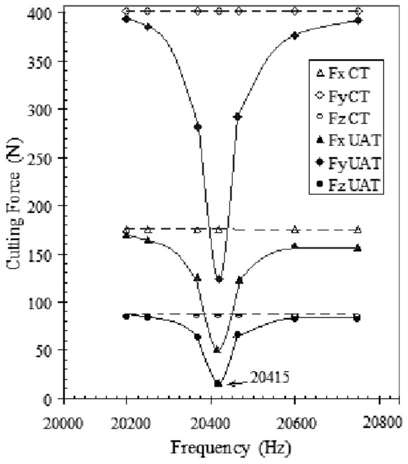
The NFLM of horn-tool assembly is reduced by any increase in the mass of the assembled parts. In addition, the changes in inclination angle do not change the main cutting force (F_y), both in conventional and vibrational oblique turning, which is in agreement with other researches [17, 18].

7. Conclusion

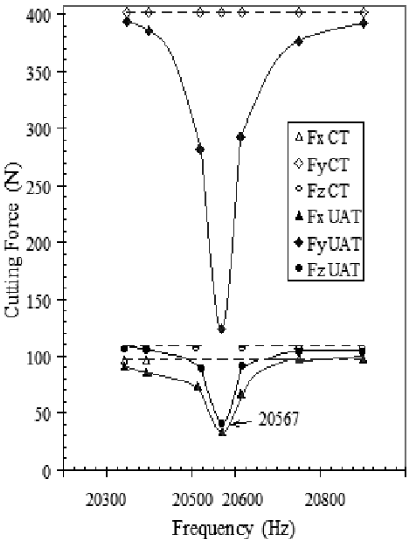
The actual turning process (common in industry, namely, oblique turning) improves surface roughness and tool life in comparison with orthogonal turning, where providing orthogonality conditions is difficult and useless. However, oblique turning has more complex geometry than orthogonal turning and therefore its theoretical and experimental analysis is more complicated. In ultrasonic assisted oblique turning, in addition to conventional machining movement, the cutting tool also vibrates, making its analytical and experimental study even more difficult. In the present study, first, the kinematics of vibrational oblique turning was presented. It was shown that applying ultrasonic vibrations to the cutting tool along the cutting velocity direction causes the tool-workpiece



i = 45 deg



i = 30 deg



i = 15 deg

Fig. 9. Changes in cutting force components with respect to excitation frequency of the horn-tool assembly in different inclination angles (tool feed rate of 0.4 mm/rev, cutting velocity of 0.53 m/s, 1 mm depth of cut and vibration amplitude of 16 microns).

interaction inside cutting zone to become more complicated compared with other setups in which the tool is forced to vibrate perpendicular to its cutting edge. To provide precise equipment for later researches, a novel vibrational system was designed in a way that it would be mostly in accordance with the assumptions made in theoretical analysis of oblique cutting mechanics. The desired vibrational setup was manufactured and then tested under different cutting and ultrasonic vibrational conditions. Experimental cutting forces were measured to show the behavior (output) of the oblique vibrational horn in limited range of excitation frequencies including the natural frequency of longitudinal mode (NFLM of the horn). The considerable reduction of cutting forces at the resonance frequency of oblique vibrational system conformed properly with design predictions. Therefore, the presented equipment can be successfully employed for other studies and industrial applications of ultrasonic assisted oblique turning process.

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