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Research Paper

Design, Analysis and Manufacturing of a Bone Cutting Ultrasonic Horn-Tool and Verification with Experimental Tests

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Abstract. Horn is one of the main components of ultrasonic cutting systems. The most important characteristics of the horn design are its resonant frequency and amplification factor. Closed-form equations can be used only for the design of simple horns and do not apply to more complex shapes like surgical tools. In This paper, a designing technique based on the finite element method and experimental tests is presented. The conventional design methods are improved, and designing a high performance surgical ultrasonic horn for bone cutting tools is facilitated. The new and complex bone cutting tool has both the knife-edge and toothed-edge, which could cut the bone easily and accurately. The investigations of cutting forces applied to the tool edges show less force in the toothed edge than the knife edge.

Keywords: Ultrasonic Horn-Tool, Bone, Finite Element Method, Cutting, Resonance Frequency.

1. Introduction

Ultrasonic energy has been provided with considerable benefits for a variety of industrial applications such as automotive, food preparation, medical, textile, and material joining [1]. In the clinical area, ultrasonic devices have been widely used in surgery, therapy, diagnosis, and a tissue dissection tool [2-4]. It has the advantages of precision, higher tissue repair, lower force, less bleeding, less lateral thermal damage, faster operation times, and fewer postoperative complications [5-8]. Schematic view of an ultrasonic bone cutting system depicted in Fig. 1.

Horn or sonotrode is one of the main elements of the ultrasonic system that affects the cutting performance of ultrasonic cutting equipment [1, 9]. The horn transfers the longitudinal ultrasonic waves from the end of the transducer (the electric energy converter to mechanical vibrations) to the cutting tool and amplifies the vibration signal at the output end of the tool [10]. The horn geometry has a significant effect on its performance. It has different profiles, but the most frequently used shapes of ultrasonic horns are: cylindrical, stepped, exponential, and tapered [11].

The material property of an ultrasonic horn is another factor that affects the maximum ultrasonic amplitude [11]. The horn material must have excellent acoustic properties and high resistance to fatigue cracking. Titanium, Monel, and stainless steel are commonly used for the manufacturing of horns. Among these alloys, titanium is preferred because of its high fatigue strength and its excellent acoustical properties, which enables it to endure high amplitude large cycles [12].

In recent years, there have been studies that have focused on investigating ultrasonic horns. Dipal et al. [13] and Behera et al. [14] discussed the different conventional shapes and profiles of horns and their materials. It was observed that it is crucial to know the amplitude and resonance frequency at every point of the ultrasonic system for desirable performance. It is also essential to the proper selection of horn material for maximum amplitude of vibration at the tool-tip. Dynamical properties of ultrasonic horns with different shapes and understanding of the relationship between the horn geometry and its material investigated by Nad et al. [15] and Qiu et al. [16]. They reported that amplitude, the amplification factor of the horn, and its resonance frequency are essential requirements for horn geometry selection.

Some articles present new designs for horns with different applications such as ultrasonic machining, tissue dissection, electro-discharge machining, and forming. Roy et al. [12], Kuang et al. [5], Shu et al. [11], and Nanu et al. [17] are among the studies that have been presented in this area. A good agreement between FEM analysis and practical analysis, a better magnification factor while undergoing less stress than conventional horns, and higher efficiency were obtained. As a result, still different processes can be improved with better new designs for ultrasonic horns and tools. Guiman et al. [18] performed an optimization of the shape of an ultrasonic horn. The optimization technique led to a new shape function with space-dependent single component function and the position of the neutral points. The obtained horn was analyzed using theoretical and experimental methods. The tests and numerical simulations confirm the hypothesis used in the horn optimization design.

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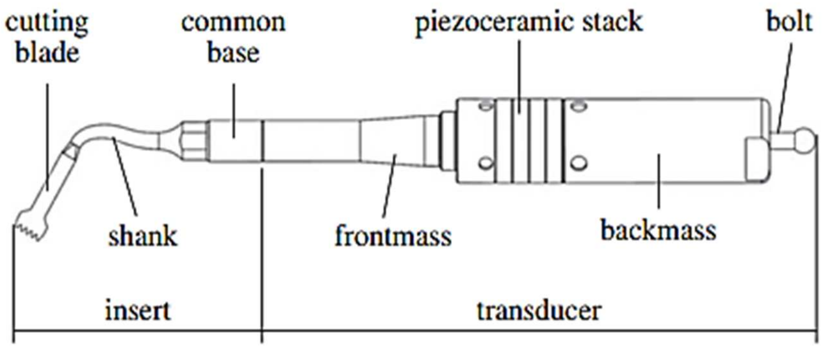


Fig. 1. Schematic view of an ultrasonic bone cutting tool

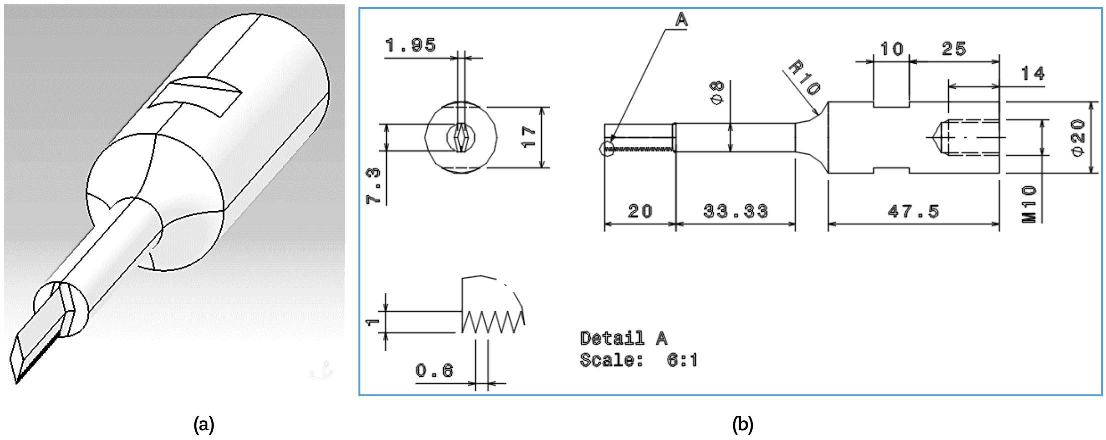


Fig. 2. Horn-Tool, **(a)** 3D Model, **(b)** Dimensions (mm)

The literature review [19-24] reveal that the designing, modeling, and analysis of ultrasonic horns with analytical, theoretical, or FEM models have been studied previously. However, these studies usually involved horns with simple shapes or often in the fields of machining or welding, but no work has been carried out using more complex shapes in the surgery, and bone cutting filed.

The closed-form equations such as "Webster's Horn Equation [25]" can be used for a large number of cases in the horn design [15]. Nevertheless, these equations are useful in obtaining classical solutions like cylindrical, conical, and exponential horns, which are solid, have a circular cross-section, and simple shapes, but no work has been carried out using the more complex shapes like the surgical horn and tools. In these cases, the finite element analysis (FEA) is a useful tool for simulation and analysis of complex horns and tools.

The current study aims to design a new ultrasonic horn for a sophisticated bone cutting tool based on FEM analysis. FEM simulations are used to determine the resonance frequency of the horn, the amplitude of vibrations at the tool end, and the distributed stress on the horn. One of the advantages of this research is the integrity and connectivity between tool and horn, which enhances the performance of the ultrasound system. Manufacturing of the designed horn and its verification is another purpose of the presented work. Finally, the proposed tool is applied for cutting bone; the performance of its edges is evaluated and compared between force distributions on each edge of the tool. With the suggested tool, surgeons can choose the location of the incision and the shape of the tool edge. Also, it is a well suitable selection for bone cutting in different surgical operations such as orthopedic, dentistry, and so one.

2. Finite Element Modeling

The traditional methods for the design of a horn are based on the equilibrium of an infinitesimal element under elastic action and inertia forces and then integrates over the horn length to attain resonance [26]. The finite element method (FEM) is used to model, analyze, and predict the efficiency of real physical systems [11]. An initial attempt to apply the FEM to the horn design was performed by Coffignal [27]. It was assumed that the horn and its tool worked as one body having a non-uniform scale in their analysis. FEM is one of the most flexible and powerful tools available for solving horn design problems [28, 29]. FEM can be applied to systems with any geometric configuration or boundary condition. Firstly, the modal analysis by using ABAQUS software is performed to find the natural frequencies of the ultrasonic horn. Then, the amplitude magnification of the horns is obtained through harmonic analysis. Finally, the results of the FEM models are examined.

2.1 Modeling

CATIA V5-R20 software was used to design the model of the horn and other necessary devices in the ultrasonic system. This modeling was related to the horn and transducer that are shown in Fig. 2 and 3. The horn's end was designed similar to the bone cutting tools. One side of this tool was sharp (similar to a knife), and the other side was toothed (similar to a saw). This was made from the titanium (Ti6V4Al) and was called Horn-Tool. ABAQUS 6.14-1 software was used in finite element simulations. The Horn-Tool and the transducer models were imported in the ABAQUS software from the CATIA software.

2.2 Material Property

The material properties of the Horn-Tool and the transducer components are shown in Tables 1 and 2. In the ABAQUS software, piezoelectric were defined as piezoelectric materials, and other components were defined as homogeneous and isotropic solids [30].

Table 1. Material properties of the Horn-Tool and the transducer components [31-33]

Part Name / Material	Poisson Ratio	Elastic Module (GPa)	Density (Kg/m³)
Horn - Tool / Ti6V4Al	0.342	112.8	4450
Connecting Bolt& Back Bolt / Milled Carbon Steel (High Strength)	0.29	201	7880
Matching / Al 7075-T6	0.33	73	2887
Plates / Cold Worked Cupper	0.35	106	8975
Backing / Stainless Steel 304	0.292	203	7888

Table 2. Piezoelectric properties [34-36]

Property	Magnitude or Matrix
Density (Kg/m³)	7640
Elastic Matrix (GPa)	$\begin{bmatrix} 132.2 & 69.8 & 72.7 & 0 & 0 & 0 \\ 69.8 & 132.2 & 72.7 & 0 & 0 & 0 \\ 72.7 & 72.7 & 115 & 0 & 0 & 0 \\ 0 & 0 & 0 & 30.1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 26.1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 26.1 \end{bmatrix}$
Piezoelectric Coupling Matrix (Stress Coefficients) (Coulomb/m²)	$\begin{bmatrix} 0 & -5.2 & 0 \\ 0 & 15.1 & 0 \\ 0 & -5.2 & 0 \\ 12.7 & 0 & 0 \\ 0 & 0 & 12.7 \\ 0 & 0 & 0 \end{bmatrix}$
Dielectric Matrix (farad/m)	$\begin{bmatrix} 730 & 0 & 0 \\ 0 & 635 & 0 \\ 0 & 0 & 730 \end{bmatrix} \times 10^{-7}$

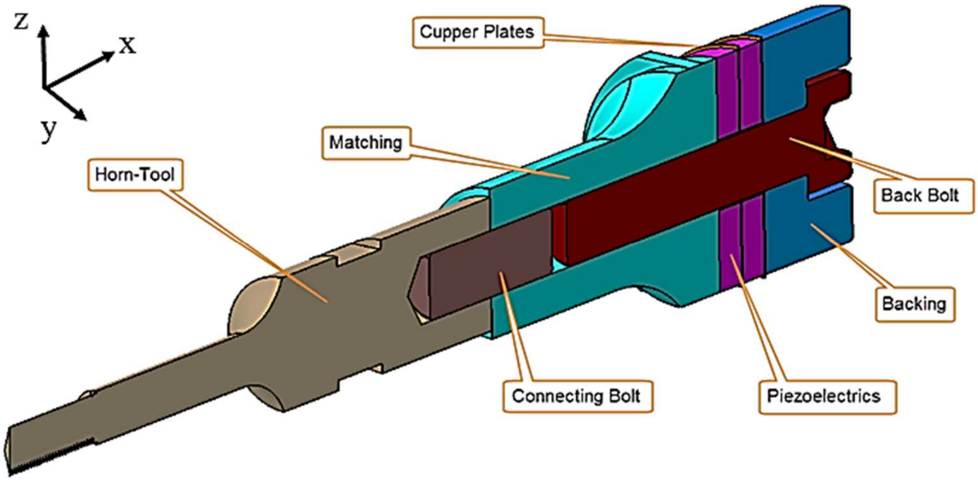


Fig. 3. Schematic view of the Horn-Tool and transducer assembled

2.3 FEM Analysis Steps

Two steps were taken to solve the problem. In the first step, a modal analysis was used to obtain the natural (resonance) frequencies of the set and its vibrational modes. For this purpose, Linear Perturbation (Frequency analysis and Lanczos solver) were used [14]. In this analysis, all vibrational modes and natural frequencies of the ultrasonic systems (transducer and Horn-Tool) in the range of 20 to 40 kHz were obtained. This frequency range is mainly used for ultrasonic bone cutting. In the second step, in order to get the system response against external harmonic, the harmonic analysis in the form of Linear Perturbation (Steady-State Dynamic) was performed [30].

2.4 Boundary Conditions and Mesh

As shown in Fig. 3, all parts of Horn-Tool and transducer had circular cross-sections and are symmetrical relative to the XZ plane. As a result, the parts were modeled according to the symmetry plane. This will reduce the volume and cost of the calculations and increase the speed of simulations. Since the beginning of the Horn-Tool is in contact with the transducer and its end is free, in the first step of the analysis, the Free-Free boundary condition for the beginning and end of the Horn-Tools was considered [15, 37].

In the second step of the solution, that requires the harmonic stimulation exerted to the Horn-Tool. So, a displacement equal to 10 microns (approximately the same as transducer output vibration amplitude) was applied in the longitudinal direction of the Horn-Tool. This boundary condition was periodic (sinusoidal), and its frequency was similar to the generator frequency (28,000 Hz). Due to geometric changes existing in the shape of the ultrasonic set parts, the Free technique mesh generation and Tet Elements was used. The size and degree of elements were studied in different setups, and the optimal model was obtained and is reported in the results section.

Table 3. The various states of the size and degree of elements created on the Horn-Tool

No.	Element Seed (m)	Number of Elements	Element Type	1st Longitudinal Natural Frequency (Hz)	Calculation Time (s)
1	0.008	1073	C3D4	29175	11.79
2	0.006	1512		29214	11.95
3	0.004	2832		28850	13.79
4	0.002	11305		28660	15.78
5	0.001	58281		28208	35.95
6	0.008	1073	C3D10	28536	13.57
7	0.006	1512		28529	13.69
8	0.004	2832		28515	15.84
9	0.002	11305		28504	28.07
10	0.001	58281		28502	176.88

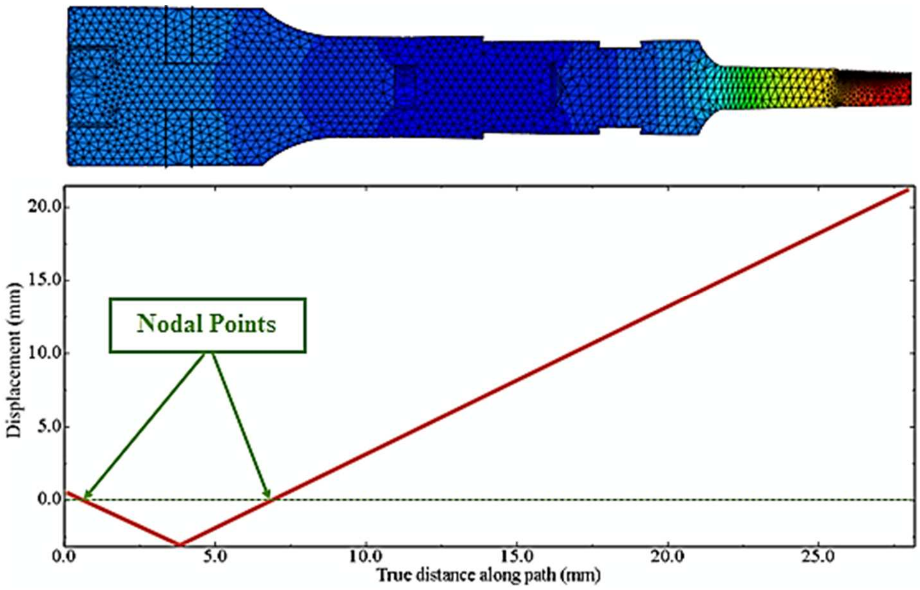


Fig. 4. The result of modal analysis on the transducer and the Horn-Tool assembly
Mode2=Longitudinal / F=28011 (Hz)

3. Results

3.1 Modal Analysis

First, by assuming a fixed geometry for the Horn-Tool, the optimal model for the size and degree of elements acquired so that the results of the analysis had both acceptable accuracy and low computational cost. According to the [30], if less than a 5% difference would have existed between the results of the elements changes, the element with less computational cost is preferable. Table 3 shows the various states of the size and degree of elements created on the Horn-Tool. Finally, based on the simulation results, a 10-node tetrahedral element (C3D10) with a 2 mm size (seed=2 mm) were selected for analysis. The selected element type and its grade corresponded to the research [14, 38].

Usually, the horn alone is investigated in most papers about horn design for various purposes and applications [12, 22, 23] while an ultrasonic setup containing transducer, horn, and tool. These parts should be analyzed together and have the same resonant frequency. A hole should be created at the beginning of the horn to create a connection between horn and transducer. Through this hole and with a screw, the horn's connection to the transducer takes place. In the traditional design, this hole and screw were not considered, but in the FEM method, it was possible to consider them [12, 22, 23]. The results of the analysis showed that accurate design was performed on this ultrasonic complex (transducer and Horn-Tool). The nodal point in the analysis is a point with a zero displacement (Fig. 4).

3.2 Harmonic Analysis

The harmonic analysis was performed to obtain the response of the ultrasonic system to external excitation. For this purpose, a periodic displacement of 10 microns amplitude was considered into the beginning of the Horn-Tool (1):

$$\begin{gathered} \textit{Periodic Amplitude}=A\sin(\omega t+t_0) \\ A=1\ ,\ f=28000\ (Hz)\ ,\ t_0=0\ ,\ \omega=2\pi f=175929.2\ (rad/s) \end{gathered} \tag{1}$$

Ten microns is almost equivalent to the transducer output displacement that is transmitted to the Horn-Tool. The Horn-Tools response to this stimulation is shown in Fig. 5. In the longitudinal resonance frequency, maximum displacements of 28,200 Hz were seen at the tip of the Horn-Tool. According to these results, the Horn-Tool amplitude gain was more than seven times. The distribution of stress created in the horn under these conditions is shown in Fig. 6.

In the frequencies before and after the longitudinal resonance frequency, the distribution of stresses is very negligible (about zero), while at the longitudinal resonance frequency, this is very high (Fig. 6).

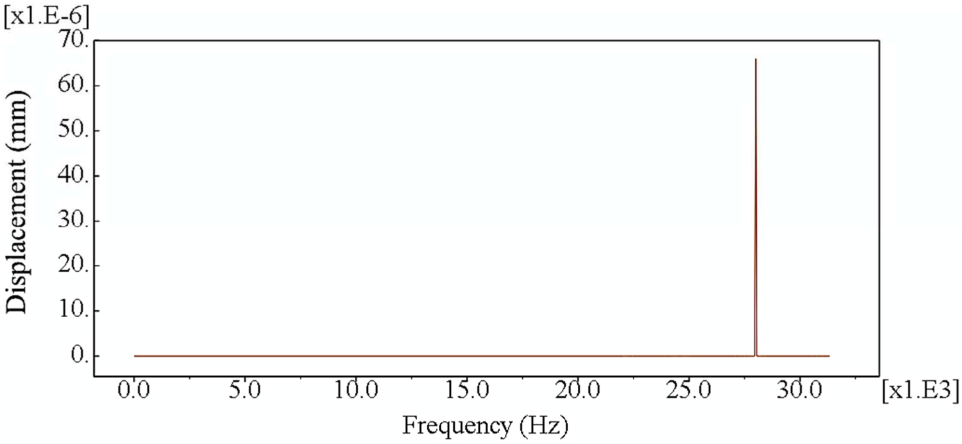


Fig. 5. The Horn-Tool response against external periodic stimulation

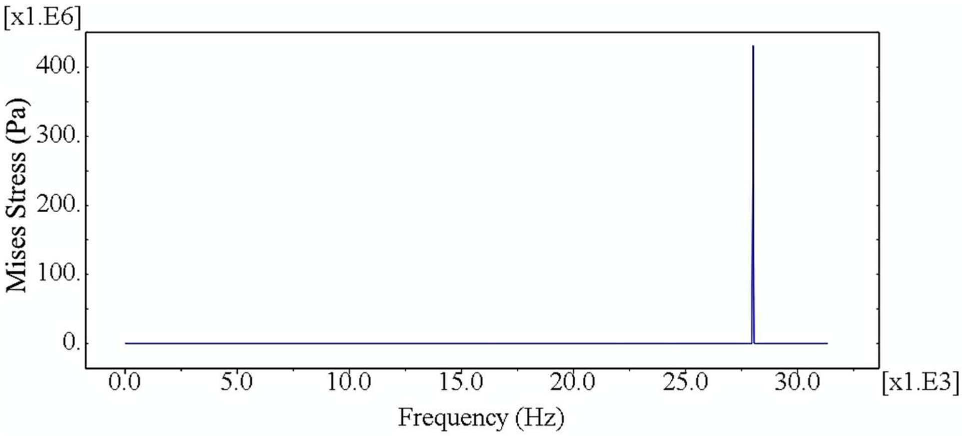
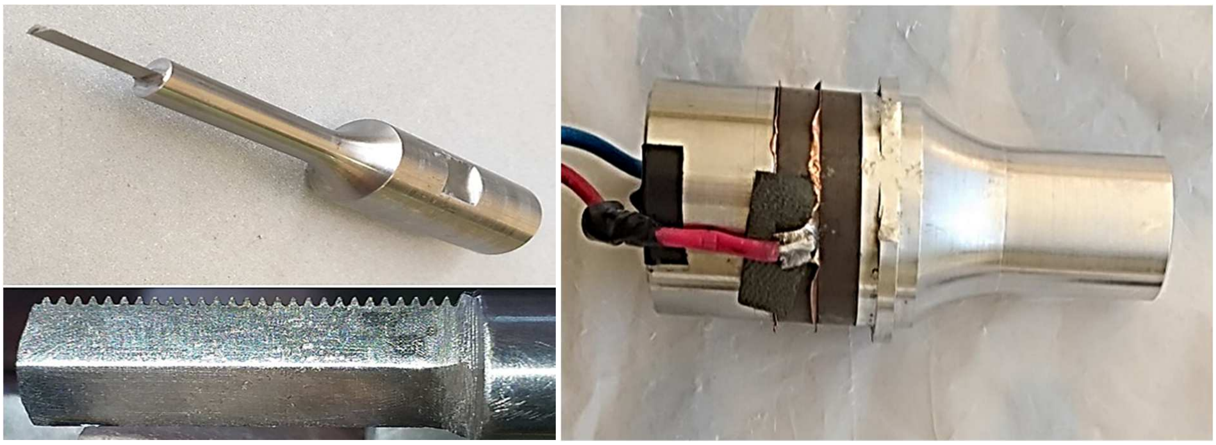


Fig. 6. Mises stress distribution at stress concentration point of the Horn-Tool against external periodic stimulation



(a) (b)

Fig. 7. (a) The manufactured titanium Horn-Tool, **(b)** The manufactured 28000 (Hz) transducer

3.3 Experimental Results

Based on the analysis and the finite element simulations, the transducer and the Horn-Tool were produced using manual and CNC machines. These parts are shown in Fig. 7. With the frequency analyzer device (Impedance Analyzer PV520A produced by BANDEAR ELECTRONICS CO.), the natural frequencies of the manufactured parts were checked. The investigation results are shown in Fig.8. As the results show, with less than1% error, the frequency of the ultrasonic set was consistent with the finite element simulation results.

The manufactured Horn-Tool was used in research work about bone cutting that their setup is shown in Fig. 9. The Horn-Tool assembled to the transducer, and this package was installed into the fixture from the transducer nodal point. The fixing fixture was attached to the CNC column. The bovine femur bone was selected for cutting samples because of its many mechanical properties the same as human bone [39]. The bones were kept by the clamp, and the clamp was laid on the dynamometer sensor. This pack was fastened on the CNC table. The tool was tangent on the bone surface and fix. The CNC table had reciprocating and downward automatic movements in the x and the z-directions, respectively, and was fixed in the y-direction. The force applied to the tool in 3 directions (x, y, and z-direction) was measured with a dynamometer.

The tool had two edges, the one edge like to knife and the other edge like to saw. This instrument was used in the different cutting of bovine femur bone. Samples of cutting bones are depicted in Fig. 10.

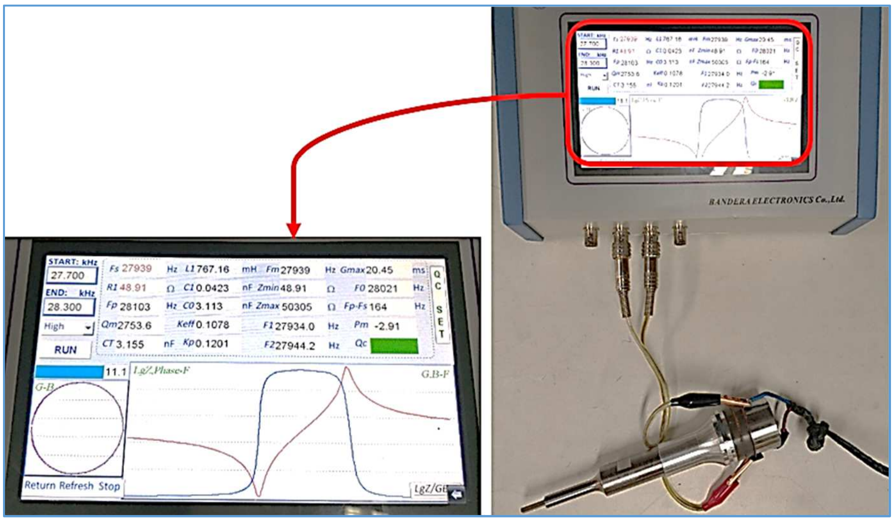


Fig. 8. Frequency test of the transducer and the Horn-Tool assembly

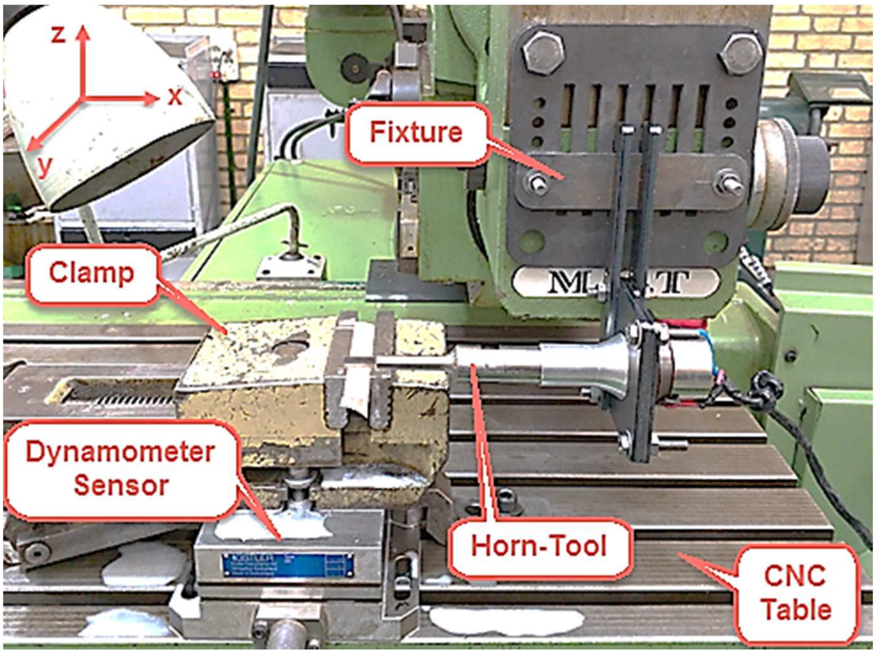
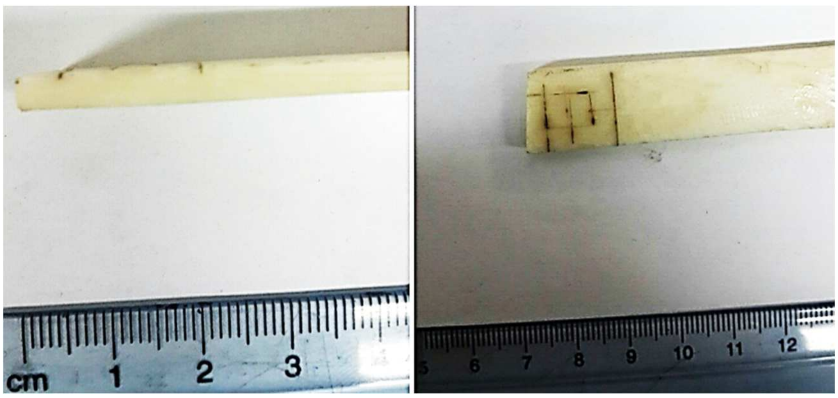


Fig. 9. The ultrasonic set for bone cutting



(a) (b)

Fig. 10. The samples of cutting bone, **(a)** side view, **(b)** front view

3.3.1 The knife-edge of the tool

The experiments were performed in two modes: cutting with ultrasonic vibrations (ULV) and cutting without ultrasonic vibrations (WULV). In the WULV, the knife-edge of the tool, although it was sharp, could not cut the bone and only scratched it. In the ULV, the knife-edge of the tool could partially cut the bone. In this state, the Force-Time curves of the ULV and the WULV are depicted in Fig. 11.

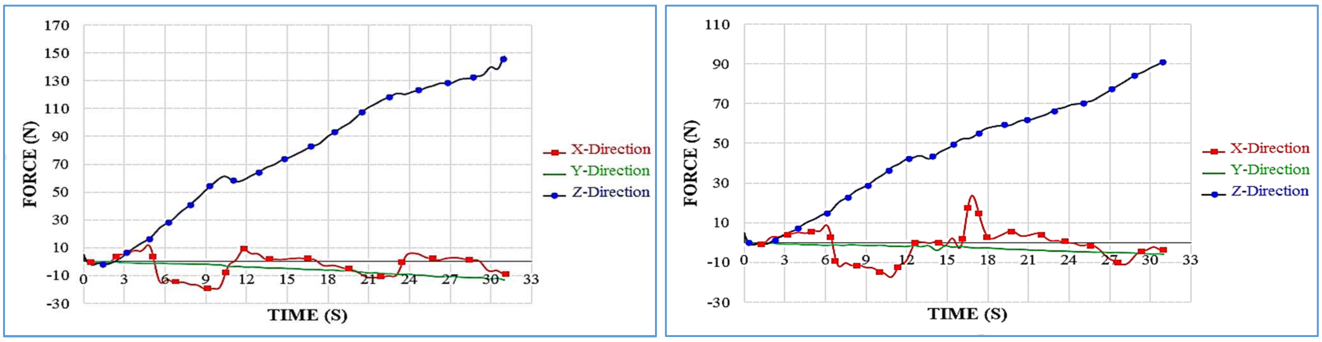


Fig. 11. The Force-Time diagram of the knife-edge of the tool, **(a)** WULV, **(b)** ULV

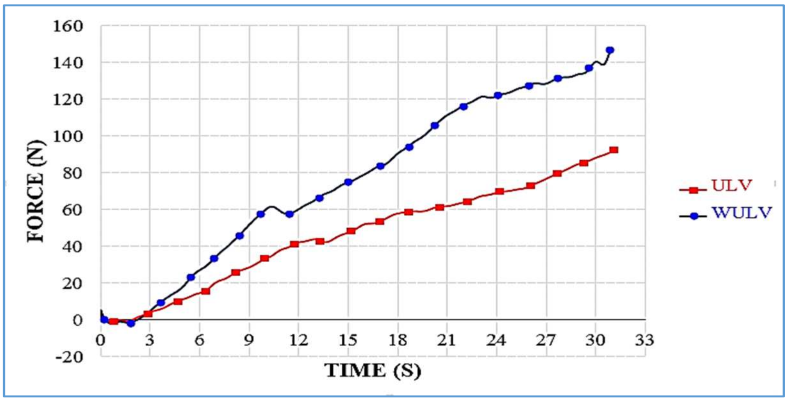


Fig. 12. The comparison of the z-direction force of the knife-edge of the tool in ULV and WULV

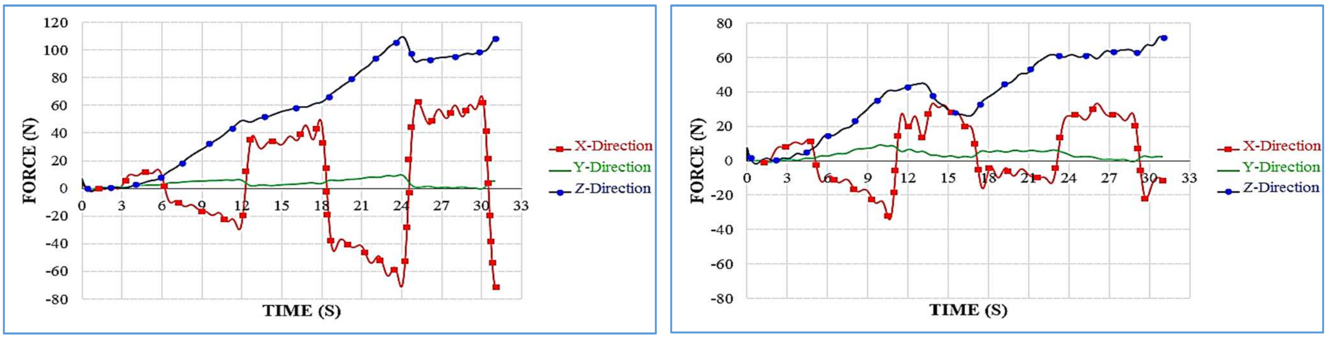


Fig. 13. The Force-Time diagram of the toothed edge of the tool, **(a)** WULV, **(b)** ULV

According to Fig. 11, in both cases, i.e., the ULV and the WULV, the force in the x and y-directions are negligible (due to the reciprocating motion of the CNC table, the force in the x-direction has negative and positive values) and in the z-direction, the cutting force increases with increasing depth of the cut. A comparison of results shows that the forces in x and y-direction in both ULV and WULV are almost identical, but the z-direction force in the WULV greater than of the ULV (Fig. 12).

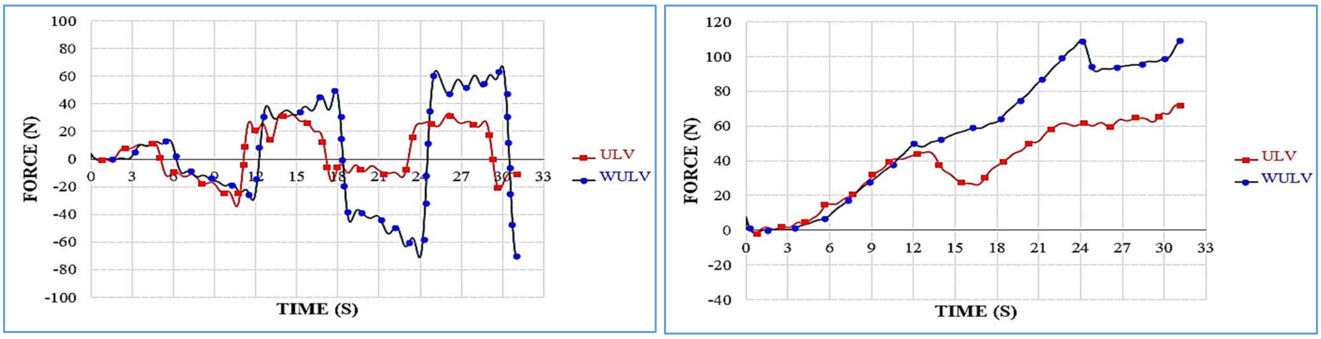
3.3.2 The toothed edge of the tool

In the same test conditions (bone, speed of CNC table, etc.), the toothed edge of the tool was evaluated. In the WULV, the tool was able to cut the bone somewhat, but a relatively large force was applied to the tool in the cutting direction. However, in the ULV, the toothed edge of the tool was well able to cut the bone with less force and more quickly. In this state, the Force-Time curves of the ULV and WULV are depicted in Fig. 13.

According to Fig. 13, in both cases, i.e., the ULV and the WULV, the force in the y-direction is negligible, and in the x-direction is periodic (due to the reciprocating motion of the CNC table) and approximately increases with increasing depth of cut. In the z-direction, by changing the direction of the CNC table movement, the force applied to the tool temporarily decreases, but in the overall cutting process, this force increases with increasing depth of the cut. In this case, the same as the knife-edge of the tool, a comparison of results shows that forces in the y-direction in both ULV and WULV are almost equal, but the x and z-direction force in the WULV greater than of the ULV (Fig. 14).

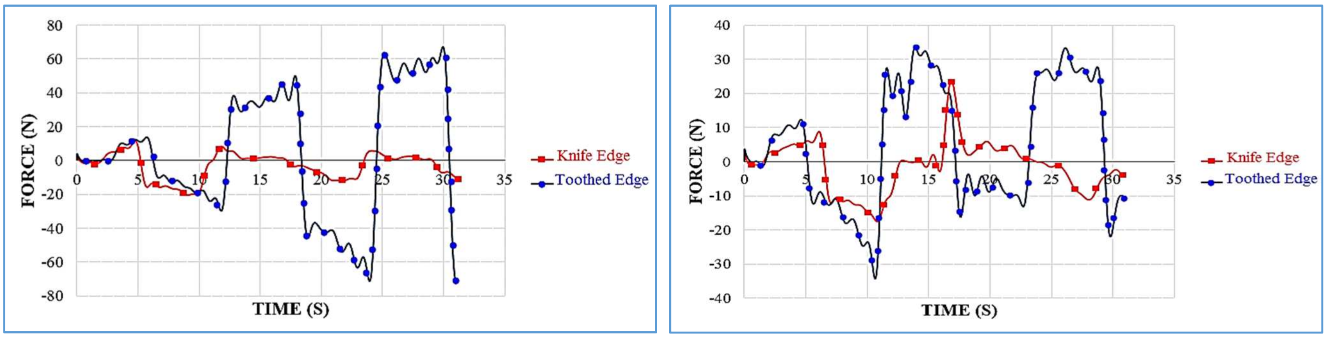
4. Discussion

The experimental results show that the force in the y-direction on both edges of the tool in ULV and WULV is insignificant and approximately equal. Because of the teeth, a greater force in x-direction was applied to the teethed edge of the tool rather than on its knife-edge, which was present in both ULV and WULV cases, and is shown in Fig. 15. However, when the ultrasonic power was applied (ULV), the x-direction forces were closer together at the two edges of the tool.



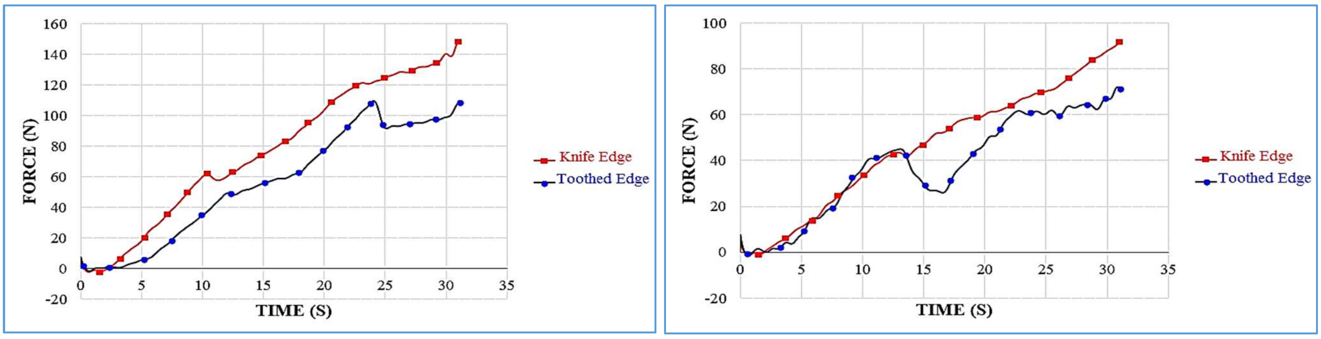
(a) (b)

Fig. 14. The comparison forces of the toothed edge of the tool in ULV and WULV, **(a)** x-direction, **(b)** z-direction



(a) (b)

Fig. 15. The comparison of x-direction force of the toothed edge and knife-edge of the tool, **(a)** WULV, **(b)** ULV



(a) (b)

Fig. 16. The comparison of z-direction force of the toothed edge and knife-edge of the tool, **(a)** WULV, **(b)** ULV

The exerted forces on the tool edges in the z-direction, which indeed was the main cutting force, were different from the x-direction forces. In both ULV and WULV tests, the less force was applied to the toothed edge of the tool. This subject is depicted in Fig. 16.

Further research in the field of cutting the bone in the different states of loading and cutting speed is in progress.

5. Conclusion

The closed-form equations were considered appliable only for the design of simple horns. It was observed that it is improper to utilize them to more complex shapes like surgical horns and tools. In this study, to facilitate designing a high performance surgical ultrasonic horn for bone cutting tools, a new ultrasonic Horn-Tool for cutting bone was designed, manufactured and verified with experimental tests. The following results were conclusive:

1. Horn correct design plays a significant role in the quality and efficiency of the cutting process.
2. Theoretical and analytical equations apply to design simple and not complex horns. By developments in the field of finite element software, if the horn or ultrasonic instrument is complex, it can easily be designed and simulated using modal and harmonic analyzes and predicted their vibrational behaviors.
3. According to the design, Horn-Tool was constructed and examined. The designed ultrasonic horn had a cutting tool with different edges at its end (Knife-edge and toothed edge). The results of experimental tests and FEM simulation of Horn-Tool are in good agreement, and it was found that sonotrode could transmit vibrations well. The tool with both edges predicted for it was able to perform well at the cutting of a bovine femur bone with the help of ultrasonic vibration. In these conditions, the results of experiments showed that the toothed edge has a higher cutting speed and less cutting force.
4. In the design and analysis of the horn, its beginning hole and the horn connecting screw to the transducer should be considered in the modeling.
5. Since the entire ultrasonic system must have the same resonant frequency, it is better to set the transducer, horn, and tools to be analyzed together.
6. The shape and the length of a horn are obtained by experiments or rules of thumb in industrial applications; hence they expend much more materials and time. Furthermore, due to poor design, the efficiency does not reach the maximum. The finite element analysis (FEA) has high accuracy and will be able to reduce design time and production costs effectively.
7. The horn design and its manufacture require special attention. An incorrectly designed horn will impair cutting performance

and can lead to the destruction of the vibration system and cause considerable damage to the generator.

8. The results of frequency analysis differed less than 1% with FEM results that show the ability of FEM to design and accurately predict behaviors of an ultrasonic horn. This fact can greatly reduce the trial and error time for involved in horn design.

Author Contributions

M. Rezaei initiated the project, run the FEM analysis, suggested and conducted the experiments; M. Farzin and F. Ahmadi proposed the subject of research, planned the scheme, and helped in the experiments; M. Rezaei and M.R. Niroomand analyzed and explained the empirical results. The manuscript was written through the contribution of all authors. All authors discussed the results, reviewed, and approved the final version of the manuscript.

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Not applicable.

Conflict of Interest

The authors declare that there are no conflicts of interest.

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Data Availability Statements

The datasets generated and/or analyzed during the current study are available from the corresponding author on reasonable request.

Nomenclature

ω	Angular frequency [rad/s]	A	Amplitude [m]
f or F	Frequency [Hz]	t_0	Initial time [s]

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