Design and Fabrication of a Longitudinal-Torsional Ultrasonic Transducer

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Abstract
A hybrid longitudinal-torsional ultrasonic transducer is designed and fabricated in this research. The design of the transducer was performed using the FE method with ABAQUS software, with the aim of combining the longitudinal and torsional vibration modes. The transducer horn is then fabricated using a 4-axis milling machine. The PZT stacks are employed in order to excite the transducer. The transducer body is fabricated with grade 5 titanium for its appropriate mechanical properties. The transducer is then assembled and the experimental tests are carried out to measure the vibration amplitude in both longitudinal and torsional directions using an Eddy current displacement sensor. Theresults showed that the resonance frequencies of both the torsional and longitudinal modes are the same and experimental results are in good agreement with the FE results. The transducer can be used as a vibration tool for vibration assisted drilling which can produce both longitudinal and torsional vibrations.

Keywords
Longitudinal-Torsional, Transducer, Piezoelectric, ABAQUS, Numerical Simulation

1. Introduction

VAM transducers can be classified by vibration modes as below sections.

- Longitudinal
- Torsional
- Flexural
- Combined modes

Generally, these transducers use piezoelectric materials to produce initial excitation and resonating of these vibrations by their special shapes, to produce amplified vibrations for using in VAM systems [1].

Up until middle of 20th century because lack of computerized and mathematical models for developing ultrasonic transducers, progress in this field was too weak. Rosenberg concluded that only experimental models can give applicable results, so he produced a set of data which could be used to develop a procedure for modeling Longitudinal-Torsional systems[2] however, preparing a large amount of experimental models is very hard and expensive

During last two decades because of good advance in numerical methods, design in these transducers has had a noticeable development. In numerical studies, it doesn't need a lot of experimental models; by using a suitable algorithm, researchers can design a transducer enough precision.

Finite element (FE) method is used in this project as a kind of numerical methods. According to this method, to solve a problem, whole system (here it is a transducer) will discrete to small parts that are called elements. For each of these elements, material properties and boundary conditions will defined and then all achieved equation from these elements will solve concurrently. So accuracy of model depends on these elements, its definition and achieved equations solving directly [3, 4].

During 1960s and early 1970s, researchers such as Allik and Hughes proposed some FE models for three dimensional piezoelectric. These days several softwares have modules to simulate these problems. In this project ABAQUS software has been used to simulate and design this transducer [5].

Target of this study is offering a combined modes transducer that is excited in longitudinal and torsional modes concurrently. To produce torsional vibration, especially in torsional transducers, it is popular to use torsional piezoelectric rings that vibrate torsionally; but in this research, longitudinal piezoelectric rings are occupied to produce both longitudinal and torsional vibrations by some geometrical improvement.

In this project,essential questions are about design of mentioned transducer and defining that it is applicable to use longitudinal piezoelectric ring for producing longitudinal-torsional vibrations?

In details it is needed to propose new geometrical shape for this transducer to convert longitudinal vibrations for longitudinal and torsional vibrations.

In numerical studies, amplitudes and modes of produced vibrations will be investigated.

As mentioned before, transducer must be designed in a way to convert and amplify vibrations because initial excitation is weak and is in only one direction (longitudinal). So, geometrical improvement must be occupied. Some parts of transducer cannot change because changes in these parts can disable its function.

Front part or front mass is a good choice for geometrical correction. So, in this project, shape of front mass is one of the variable parameters. Another variable is material selection. Based on calculation, a material will be selected and its result will be investigated in numerical study.

Target of this project is Operation of transducer in predefined condition. According to these conditions, resonance frequencies of transducer must be found that it resonates in both longitudinal and torsional direction and has had enough amplitude. In other words, the target is finding frequency for specific transducer that vibrates in both directions and has had frequency of vibration high enough because low frequency vibrations are not applicable for VAM.

2. Geometry and Properties

A transducer has five parts totally, that almost all types of transducers include them. These are pre-stressing bolt, back mass, front mass, piezoelectric pieces and electrodes. There is an initial shape of transducer that will modify to achieve longitudinal-Torsional transducer.

2.1 Selection of Metal Parts

As mentioned above, a transducer has five parts that can be classified by their duty; piezoelectric pieces generate vibrations as vibration generator and metal parts which act as vibration transmitter. Another duty of metal parts is guiding the generated vibrations toward tool (front mass) rather than the back mass[6].

For an effective transmission of acoustic energy between these materials, acoustic properties should be matched. To ensure this, following equation must be satisfied[7].

$$Z_c = \sqrt{Z_f Z_b} \tag{1}$$

Z_c , Z_f and Z_b are respectively acoustical impedances of the piezoelectric pieces and the front and back masses. Acoustic impedance of each part is calculated by multiplying the characteristic acoustical impedance (Z_0) by the cross-sectional area of the part.

2.2 Front and Back Masses

A grade 5 titanium alloy (Ti-6Al-4V) is used for front mass and pre-stressed bolt because of its high tensile strength, high toughness even in extreme temperatures and good acoustic properties. Low carbon steel has high characteristic acoustical impedance because of its high density. As mentioned before, transducer must be designed in a way to guide vibrations toward front mass and tool. To satisfy this, characteristic acoustical impedance of back mass must be more powerful than front mass, so low carbon steel was selected for this target [8].

Front mass has exponentional curve through circular cross section. This radius reduction that creates an exponential curve is calculated by further formula:

$$r_z = r_0 e^{-\gamma z} \tag{2}$$

$$\gamma = \frac{\ln\left(\frac{r_0}{r_l}\right)}{l_e} \tag{3}$$

That r_0 is radius of front mass at large end and r_z is radius of front mass at z distance of large end (according to defined axes). r_0 is radius of front mass small end and l_e is length of exponentional curve through z axis.

Four circular grooves with a defined pitch have been made on front mass. These grooves help transducer to make more torsional vibrations from initial longitudinal vibrations.

Back mass has a cylindrical shape that its radius is equal to large end of front mass and its length depends on whole system that evaluate during analyses.

2.3 Piezoelectric Stacks

As vibration generator 4 piezoelectric pieces have been chosen to produce longitudinal vibrations. To simulate piezoelectric rings in transducer model, their properties defined in property module include dielectric, piezoelectric and elastic. These properties will be defined according to manufacturer's data.

In figure 1 disassembled transducer has been shown that it includes pre-stressing bolt, back mass electrodes, piezoelectric rings and front mass from left to right.

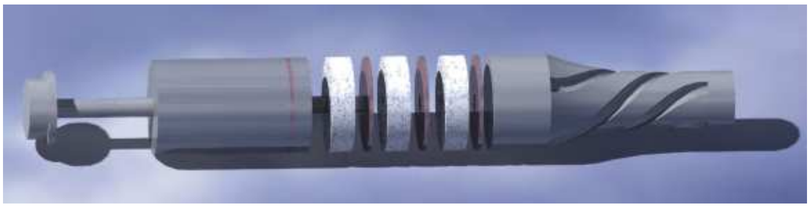

Figure1. Disassembled transducer

3. Finite Elements Simulation

Transducer simulation has two steps. In first step, that is a general static step, force of pre-stressing bolt affects transducer. In second step, that is frequency step, after effect of forces in whole model in first step, natural frequencies of transducer will be achieved.

3.1 Results

After executing simulation some natural frequencies have been evaluated for transducer. But all of these frequencies are not applicable; to be applicable, these frequencies must have had some conditions such as:

- High frequency
- Enough amplitude in longitudinal and torsional directions
- Enough separation for neighborhood frequencies

This natural frequencies was selected to transducer operate longitudinally and torsionally. Frequency mode shape and estimated displacement of transducer tip have been shown in Table 1. According to these results longitudinal and torsional amplitudes have been calculated and placed in Table 2.

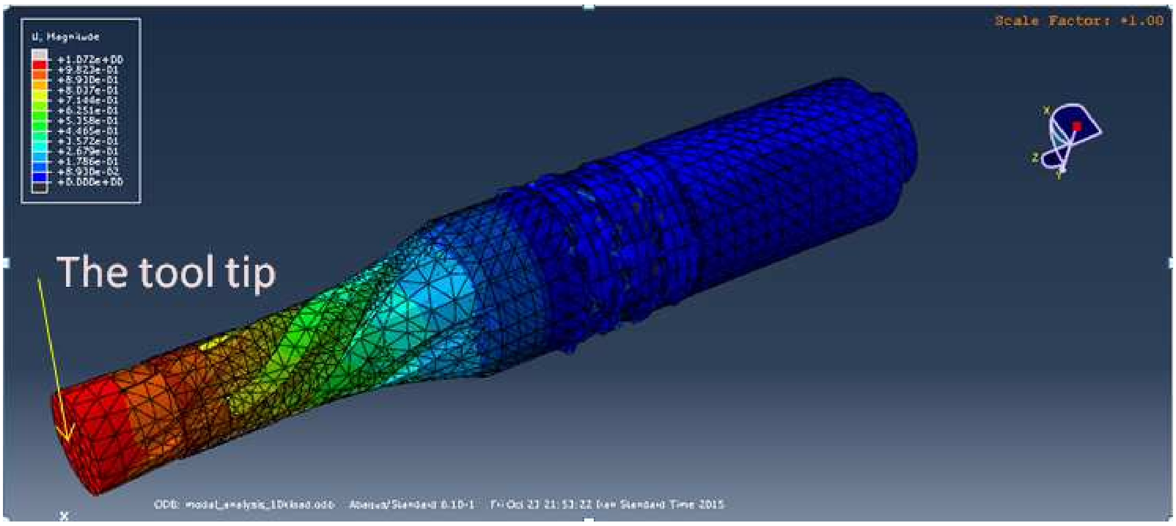

Figure2. Mode shape at 22363 Hz

Table1. Displacement of a point on face of transducer in x, y, z directions

Axes	X	Y	Z
Displacement	5.02476E-3 mm	3.06579E-3 mm	9.27710E-3 mm

Z Axes and transducer are co-axial.

Table2. Torsional and longitudinal amplitudes of transducer

Row	Torsional vibration amplitude	Longitudinal vibration amplitude
1	5.02475E-3 mm	9.27710E-3 mm

4. Experimental Tests

4.1 Preparing Transducer

A transducer based on Finite Elements results has been made as shown in Figure 5.

Figure3. Assembled transducer

4.2 Experiment Setup

To produce vibrations by a piezoelectric material, it is necessary to impose a high voltage potential on sides of piezoelectric rings. Also it is necessary that this voltage be as same as natural frequency of transducer to resonate it, so it needs a function generator and power amplifier according to figure 4. AEC-5509 Eddy Current gap sensor was used to measuring vibration amplitudes.

To measure the vibration amplitude in the axial direction, the sensor was located in front of the transducer. To measure the torsional movement amplitude, an eccentric metal strip was connected to the transducer’s tip and the sensor was located in front of this strip, so that the amount of the amplitude could be measured.

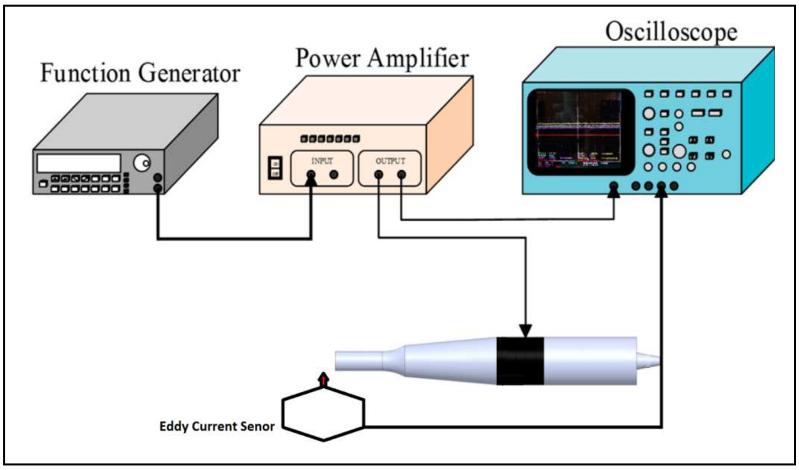

Figure4. Schematics of experiment test

4.3 Results

During operating transducer in its resonance frequency that is evaluated in FE section and measured amplitudes by eddy current sensor, these results have been gathered. Note that eddy current sensor measures amplitude by change in its electromagnetic field and report amplitude in volt term. For obtaining amplitude according to calibration tests, volts must be converted to displacement. In this sensor type, each 5 volt is equals to 1 micrometer displacement. Figures 5 and 6, relatively show longitudinal and torsional amplitudes that were measured by eddy current sensor.

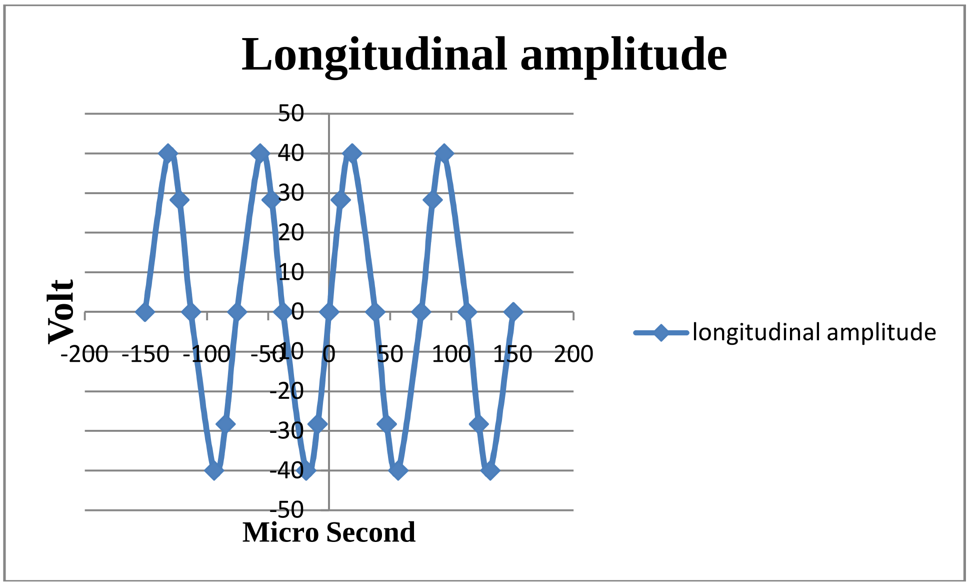

Figure5. Measured longitudinal amplitude

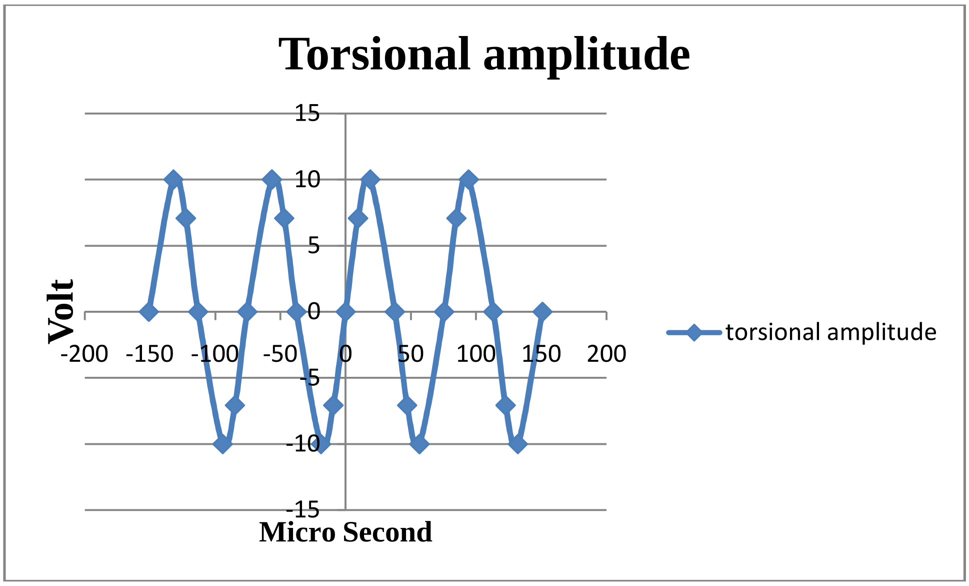

Figure6. Measured torsional amplitude

Summary of these results are given in Table 3.

Table3. Summary of results measured as longitudinal and torsional amplitudes

Row	Torsional amplitude	Longitudinal amplitude	Torsional/Longitudinal
1	2E-3 mm	8 E-3 mm	0.25

5. Conclusions

Results from made transducer in experimental setup was satisfying. Both of torsional and longitudinal vibrations in practical amplitudes were evaluated. Torsional vibrations did not completely match with numerical simulations but it was practical yet. This divergence happened because some reasons can be classified in these categories:

- **Perfect assumption in simulation**

All criterias in simulation such as material properties, boundary conditions assumed perfectly without any Homogeneity. It will be a source of errors in final results.

- **Inevitably making errors**

Although a very pernickety method was occupied to make and assemble transducer parts but it is impossible to make a perfect work piece.

Finally with considering error sources and practical results from experimental test, it can be concluded that with a simulation method in try and error process it is possible to design a practical torsional longitudinal transducer. This method of design is easier, faster and more accurate rather than analytical method.

6. References

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