A generalised approach to torsionality maximisation in longitudinal-torsional ultrasonic devices

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***Abstract* — a longitudinal-torsional vibration mode has many applications in ultrasonic systems. Obtaining this behaviour could be achieved either by coupling the longitudinal and torsional modes or by degenerating the longitudinal mode, but the results may be unsatisfactory. These methods have many disadvantages including the expense and complexity in operation, the possibility of coupling unwanted bending modes, and the low responsiveness and torsionality. In this work, we employed a geometric modification to a traditional Langevin transducer to overcome these disadvantages. This was achieved by incorporating helical slits and exponential geometry features in the front mass of the transducer. Finite element analysis and vibration response measurements show that this strategy prevents coupling of bending modes, increases responsiveness, reduces energy losses, and produces high torsionality.**

Keywords- Ultrasonic; transducer; Longitudinal-Torsional mode; mode of vibration.

I. INTRODUCTION

Ultrasonics is the science of employing high-frequency sound waves, usually in excess of 20 KHz, in different applications. These waves can be guided through a medium to produce the desired action, and based on the way the medium is displaced compared to the wave propagation direction, there are three principal modes of vibrational motion. These are namely: longitudinal mode (L) in which the medium particles vibrate in the direction of wave motion, torsional mode (T) where the particles oscillate in radial motion along the axis of wave propagation, and bending (flexural) mode (B) where the particles vibrate perpendicular to the axis of wave propagation. With the development of ultrasonic power applications, especially in motors, drilling and cutting processes, there is a need to couple these modes to produce a new vibrational motion is essential. One of the important required modes is the longitudinal-torsional mode (LT) which is a combination of longitudinal and the torsional vibration [1, 2].

There are two main methods to produce this mode in ultrasonic transducers of which the first method is coupling of longitudinal and torsional modes so that they resonate at the same frequency. To achieve this, Lin [3] used an exponential solid horn as a front mass for a transducer which has two sets of piezoceramic discs. The first set is poled in longitudinal direction to produce the longitudinal vibration and the second set is poled in tangential direction to produce the torsional vibration. These two vibration modes are then progressed through the exponential horn which has the rule of matching their resonance frequencies though equal the resonance lengths. This is achieved through precise selection of the cross-section decay factor of the horn. The two modes are then coupled at the output surface producing the desired mode. This method produce high responsiveness and high torsionality, which is the ratio of torsional response to longitudinal response at the output face. However, coupling of modes has many disadvantages which are the need to use two electric generators, the expensive type of tangential poled piezoceramics [4], the difficulty of securing the transducer within an enclosure because of the difference in the nodal position of the modes along the device [5] and finally the difficulty of keeping these two modes at the same resonance for different load conditions.

The second method is degeneration of longitudinal vibration to produce the longitudinal-torsional vibration mode. Tsujino [6] suggests that partially cutting slots along the wave path of cylindrical bar, which is excited by a longitudinal vibration mode, could produce a compound of longitudinal-torsional mode at the output surface. The idea is the boundaries of the cut slots will create helical paths, so that part of the generated longitudinal vibration wave in the piezoceramic stack will refract on these boundaries and propagate through the paths, converting into torsional vibration waves. The remaining part of the generated wave will propagate through the unslitted core of the horn, and then these two parts are coupled on the output face producing the desired mode. This method is more applicable, leads to inexpensive manufacture, needs only longitudinal excitation, and it is easy to secure the transducer through the longitudinal nodal position. However, the low efficiency of mode conversion is the main disadvantage of this method [5].

In this work, to improve the performance of the degeneration method, we employed the advantages of these two techniques in a traditional longitudinal Langevin transducer. The front mass of the transducer is designed as an exponential horn slotted helically along its length, so that when it is deformed by the effect of longitudinal motion produced in the piezoceramic stack, it tends to be untwisted and therefore degenerates the longitudinal motion into a combined longitudinal –torsional motion at the output surface.

II. NUMERICAL ANALYSIS

Finite element (FE) software, ABAQUS, is used for this analysis. Fig. 1 shows the transducer structure, which is composed of two piezoceramic discs sandwiched between two masses and assembled by a central titanium bolt. The front mass is an exponential decay bar made from titanium. Four slots are cut and spiral rotate along the bar length, the back mass is a cylindrical steel part. There are also thin copper electrodes between the piezoceramic discs to apply the excitation voltage. Materials are selected so that their acoustic impedance properties can be matched to minimise the internal reflection of waves.

Slot parameters are optimised through a FE modal analysis study. These parameters are the cutting depth and the angle of rotation along the bar. Four different depths are selected (8, 10, 12, 14) mm and the angle of rotation is chosen between (0-360) degree, Three criteria are evaluated in this study, which are the torsionality, the separation between the bending mode and the longitudinal-torsional mode (B-LT) and the separation between the torsional mode and the desired mode (T-LT). Slot parameters of the optimized model are selected based on these criteria.

A harmonic analysis is then performed on the optimised design by applying different excitation voltages. The longitudinal and torsional response of a point on the circumference of the transducer surface has been extracted for each applied voltage. The internal structural losses of the transducer have been considered by applying global damping using the Rayleigh formula. The viscous constant β is defined by the following expression:

$$\beta = \frac{1}{\omega_r Q_m}.$$

In this expression, ω_r is the modal frequency and Q_m is the overall mechanical quality factor, which is estimated at the beginning of the analysis and then corrected after doing an experimental harmonic analysis of the fabricated transducer.

III. GENERALISATION THE FE MODEL

Development in ultrasonic applications encourages scaling features of transducers to meet the wide variety of practical applications. In order to generalise the use of degeneration technique for different transducer sizes, a numerical analysis has been extended to study the effect of changing the overall transducer dimensions on the characteristic parameters. All the dimensions of optimised model are taken as relative to the piezoceramic disc thickness and then a range of differently sized transducers are modelled. Disc thickness is chosen between 1 and 10 mm and this gives different sizes of transducers in which the overall length ranges between (26-260) mm. Modal and harmonic analyses are carried out and the resonance frequencies and mode shapes are extracted. Also the responses of output surface in longitudinal and torsional directions are extracted for an excitation of 50V (pk-pk).

IV. EXPERIMENTAL ANALYSIS

The model of 5mm piezoceramic disc thickness from the numerical generalisation study is chosen to be fabricated as shown in Fig. 1. Two experimental tests are carried out, the first test is a modal analysis to extract the resonance frequencies, the corresponding mode shapes and the nodal position; the second experiment is continuous swept sine analysis using a Laser Doppler Vibrometer (Polytec CLV 3D laser vibrometer) to extract the longitudinal and torsional responses of a point on the circumference of transducer outer face. The responses are obtained for a range of excitations and the results are compared with the numerical analysis results.

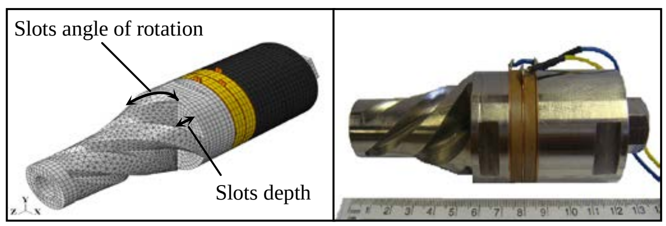

Figure 1. Numerical transducer model (left) and fabricated transducer (right).

V. RESULTS

Fig. 2 shows the numerical optimization of torsionality and mode separation as functions of slot depth and angle of slot cut along the front mass. The model is considered to be constrained at the longitudinal nodal position. The torsionality could reach up to 200% for 14mm cutting depth, but, there is a possibility to coupling with the bending mode, with only 1% of B-TL mode separation. The optimised model of 12mm cutting depth and angle 180 degree angle of rotation have more than 90% torsionality and 12% B-LT separation. The T-LT mode separation is high enough to prevent coupling of modes for most of studied models.

Fig. 3 shows the numerical results of peak responses of different transducer sizes as a function of the piezoceramic disc thickness for a 50V (pk-pk) excitation. The torsionality is not affected by the increase of transducer dimensions. This indicates that the conversion technique can be applied to a wide range of transducer sizes with the same performance. The increase of response with disc thickness is due to increase of piezoceramic disc cross-sectional area, which in turn produces higher longitudinal response in the stack.

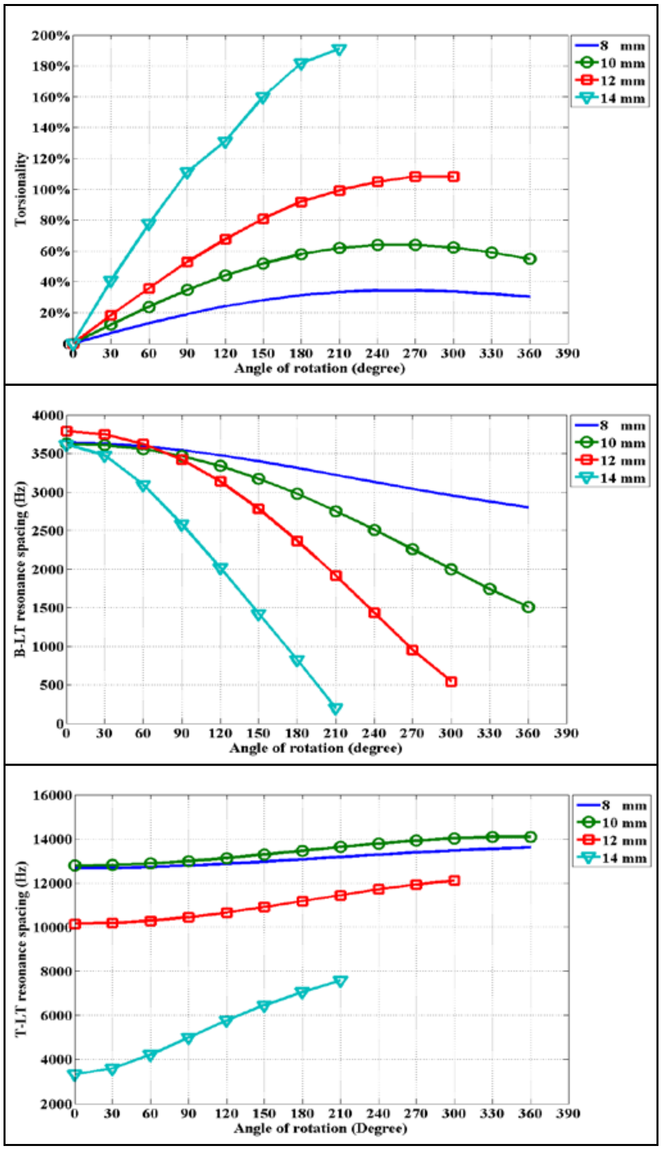

Figure 2. Optimization of torsionality and mode separation as function of slots depth and angle of cutting rotation along the front mass.

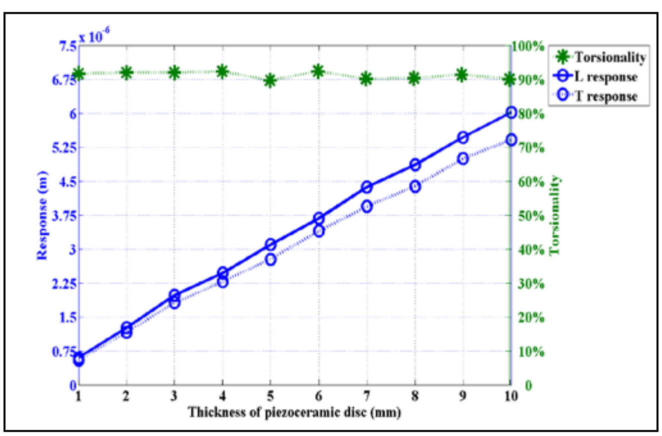

Figure 3. Peak responses (left scale) and torsionality (right scale) for different piezoceramic disc thickness.

The modal analysis results of finite element and experimental (Exp.) analyses on the fabricated model are shown in Fig. 4, where the FE model is considered free (unconstrained) in order to compare with the experimental model. The mode shape of desired LT-mode and the surrounding B-mode and T-mode of these models is obtained. The experimental results indicate that the degenerate mode resonates at 19,036 Hz and the closest B-mode is at 15,706 Hz and the T-mode is at 22,077 Hz. The separations are 17% and 16% respectively, which are high enough to prevent coupling between these modes. These results are in agreement with the FE results to within 5%.

The harmonic analysis results of FE model and fabricated transducer are shown in Fig. 5, where the peak responses at resonance and corresponding torsionalities are plotted for different excitation voltages. The torsionality is not effected by increased excitation in experimental results, the difference between experimental and numerical responses trends is due to increase of dielectric losses with excitation which is not considered in the FE model. Also, the relative motion between transducer parts at high excitation leads to increased damping, whereas the damping is considered constant over the excitation range in the FE model. The torsionality calculated by the FE analysis is higher than the experimental results at all excitation voltages. This may be related to the internal structure of the transducer, the central bolt providing less torsional than longitudinal stiffness whereas, in the FE model, the boundary conditions are simple constraining in both directions. Less torsional stiffness, and potential torsional movement between mechanical elements during operation, could be responsible for additional torsional damping and the underperformance of the mechanical system.

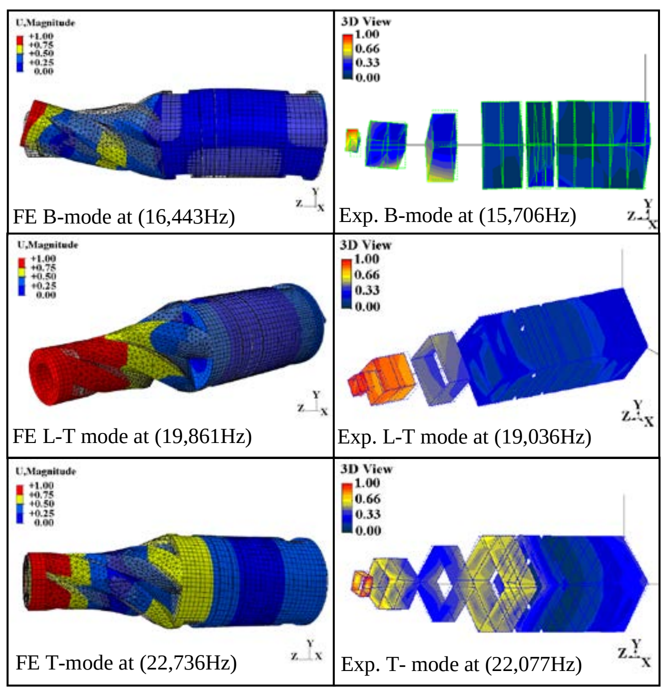

Figure 4. Numerical (left) and experimental (right) mode shapes of desired and surrounding modes of vibration.

Fig. 6 shows the experimental torsionality variation with frequency for different excitation voltages. It illustrates that, at low excitation frequencies, passage through the longitudinal resonance has a limited effect on the underlying trend in mode shape. However, at higher voltages the mode shape is influenced and torsionality at resonance is seen to decrease.

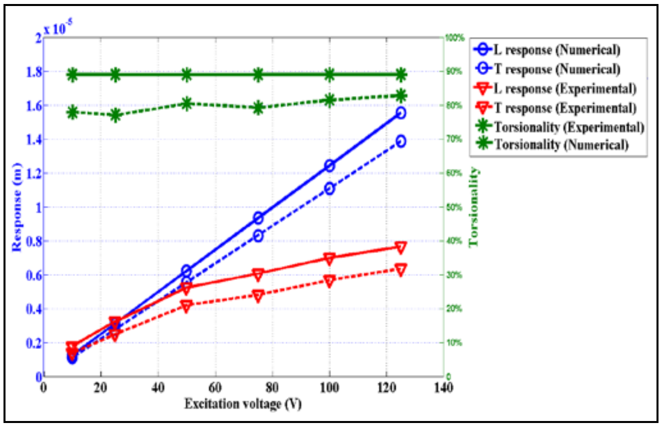

Figure 5. Longitudinal and torsional peak responses (left scale) and torsionality (right scale) for different excitation voltages.

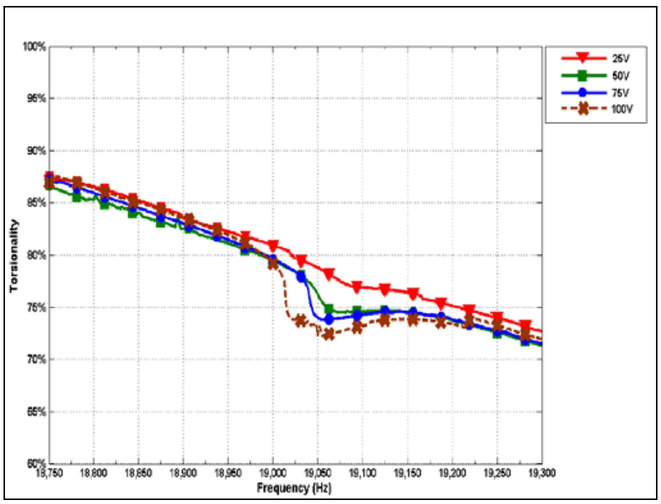

Figure 6. Variation of torsionality with excitation frequency for different excitation voltages.

VI. CONCLUSION

Improving longitudinal-torsional mode generation through geometric modifications has been studied. Maximising of responsiveness and torsionality is achieved by incorporating helical slits and exponential geometry features in the front mass of a traditional Langevin transducer. Separation between the desired mode and unwanted bending modes is also improved. Numerical analysis is employed to study the effect of geometric dimensions, variation on performance and the ability to use this technique for different ultrasonic applications. Also experimental analyses are used to verify the numerical results for selected model and shows good agreement with the numerical results.

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