Optimisation of the longitudinal-torsional output of a half-wavelength Langevin transducer

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***Abstract* —Numerous ultrasonic applications, such as high-frequency/low frequency drilling, require or can benefit from the inclusion of some torsional vibration behaviour within a primarily longitudinal pattern. Producing longitudinal-torsional (LT) vibration in a Langevin transducer using the mode degeneration method tends to give more robust results than the competing mode-coupling approach, and this work is concerned with optimizing the relative strengths of the longitudinal and torsional responses within the context of a half-wavelength Langevin transducer. Using numerical and experimental techniques, the output of such a system is predicted across a range of geometries and compared to experimental results obtained through laser vibrometry.**

Keywords- Ultrasonic transducer; Longitudinal-Torsional vibration.

I. INTRODUCTION

Longitudinal-torsional (LT) vibration is utilised in many ultrasonic applications such as ultrasonic motors, ultrasonic welding and ultrasonic drilling [1-3]. This motion is mainly generated by two methods: coupling between the longitudinal (L) and torsional (T) modes, and the degeneration of the L mode. These methods are employed in Langevin transducers which consist of piezoelectric element(s) sandwiched between front and back masses, a mechanical prestress arrangement, and electrodes between the piezoelectric elements to apply the electric field [4, 5]. Although the coupling method can produce high torsionality, which is the ratio of torsional to longitudinal response at the output surface, it has many design difficulties which make it less preferable in ultrasonic applications [6]. The degeneration method is less complex and more easily applicable, but it requires an increase in torsionality to meet various ultrasonic applications' demands.

The degeneration method is based on geometric modifications to the waveguide, which is divided into two regions. The first region is dominated by the L wave and represents the solid core of the waveguide, permitting part of the vibration to pass unchanged to the tip of the horn. The second region is concentric with solid core but contains helical slits, meaning that the remainder of the vibration must follow a spiral path and thus takes on a torsional aspect. The two parts of the wave are then recombined near the output surface of the waveguide to generate the desired LT motion. The rate of wave conversion is mainly dependant on the cross-section of the spiral paths and the helix angle. Another important parameter in designing the LT waveguide is the frequency separation between the desired LT mode and the surrounding flexural (F) modes. As the slits reduce the flexural stiffness of the waveguide, it is important to ensure sufficient frequency spacing between these modes to prevent unwanted coupling.

In the current study, we employ an exponential waveguide to improve the torsionality of the degeneration approach. The selection of an exponential horn has many advantages: it produces a higher gain than linear taper, the relatively small area of the output surface makes it suitable for precise ultrasonic applications, and the smooth decay of cross-section prevents stress concentrations and wave reflection [7]. The two regions of the waveguide provide a clear distinction between the parts of the horn concerned with transmission of the longitudinal wave and development of the torsional shape.

II. NUMERICAL ANALYSIS

A half-wave Langevin transducer is designed where the materials and dimensions of the parts are selected based on the acoustical impedance matching between them [8]. The front mass is an exponential waveguide made from 6/4 titanium alloy and the back mass is a steel cylinder, where the length is calculated by applying the principles of a plane stress theory [9]. The piezoceramic discs are PIC 181, which is a modified PZT with a high mechanical quality factor and Curie temperature that makes it suitable for resonant ultrasonic applications [10]. The discs are axially poled and sandwiched by copper electrodes.

Fig. 1 shows a schematic of the initial design of a half wavelength transducer. The longitudinal dimensions of the parts are calculated based on the one-dimensional wave equation where a nodal plane divides the model into two sections. The length of the front section is calculated based on the propagation of longitudinal acoustic waves in tapered bars [11], the back section is a combination of the piezoelectric stack and the back mass, and the piezoceramic is selected based on the required application. The plane stress wave equation can be used to calculate the back mass length [9]:

$$tan\left(\frac{\omega\ a}{v_c}\right) tan\left(\frac{\omega\ b}{v_{st}}\right) = \frac{Z_c}{Z_{st}}.$$

Where ω is the resonance frequency in rad/sec., Z_c, v_c, Z_{st} and v_{st} are the acoustic impedances and the speed of sound in ceramic and steel respectively, a is the length of the piezoceramic stack, which can be found from the number of discs, and b is the back mass length which can be calculated from the above equation for a range of resonance frequencies as shown in Fig. 2. A 60 kHz resonance is selected as an initial operating frequency where the back mass is 5 mm long.

In order to study the effect of the slitting technique on the transducer performance, three different cuts are suggested to slit the front mass: a rectangular cut, a trapezoidal cut, and a quarter circle cut. These cuts are lofted and revolved and are shown in Fig. 3, the depth and cross-sectional area of the slots are equal and the total rotation angle of the cut, along the axis of the transducer, is selected between 0° and 360° where 0° represents a straight cut parallel to the axis and 360° represents a complete rotation. A modal analysis is performed using a finite element (FE) code, ABAQUS, to calculate the resonant frequencies of the LT mode and the surrounding modes, the torsionality, the location of the nodal plane, and the amplitude ratio between front and back masses.

The FE model is created such that the metal parts are meshed with three-dimensional continuum elements of second order which have 20 nodes (C3D20R), each node having six degrees of freedom, three for translation and three for rotation. The piezoelectric material is meshed by piezoelectric solid elements (C3D20RE) where the nodes have, besides the translations and rotations, an additional electrical potential [12]. The mesh density is chosen through a convergence test of the eigenfrequencies and corresponding amplitudes along the model.

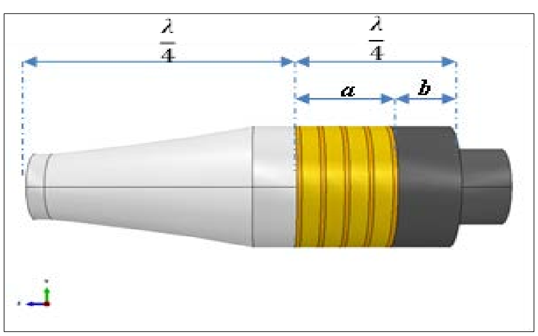

Figure 1. Schematic of the initial transducer design .

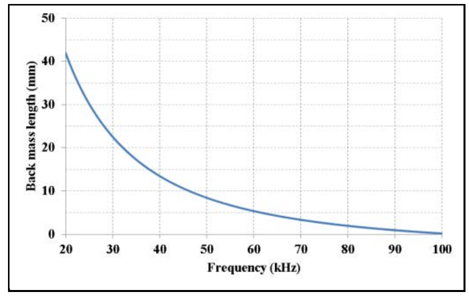

Figure 2. Variation of back mass length with resonant frequency.

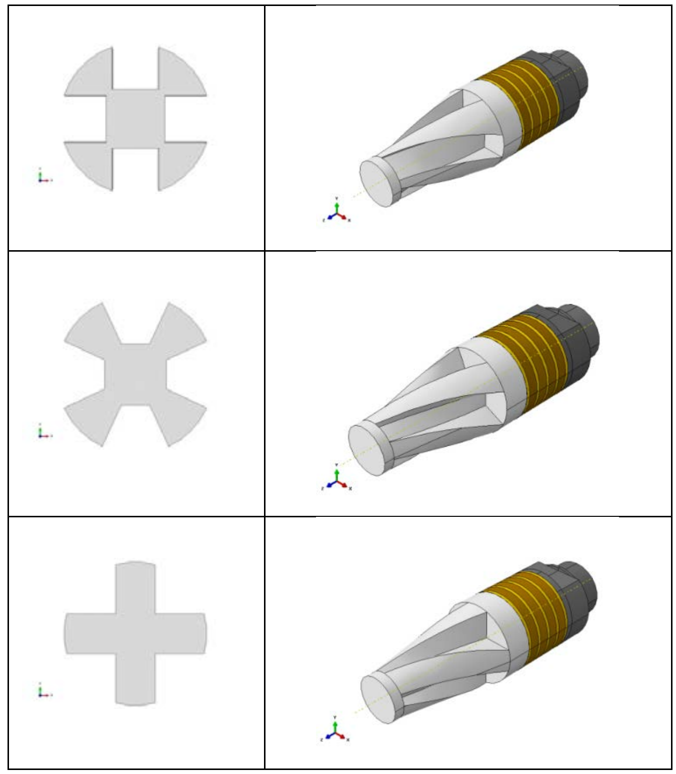

Figure 3. Cross-sectional area of rectangular, trapizoidal and quarter circle cuts with the models they produce.

The results are presented in Fig. 4, where the torsionality is calculated from the torsional and longitudinal amplitude at a circumferential point on the output surface, and suggest that increasing helix angle leads to an increase in torsionality up to a certain critical value. The rectangular cut produces the highest torsionality, 170%, at 240°, but the separation between LT mode and the F mode is only 3%. This gives a high possibility of modal coupling during operations. The trapezoidal cut produces 140% torsionality at the same helix angle but with only 5% mode separation, which is not a significant improvement. However, the quarter circle cut yields a torsionality of 102% at 260° and the mode separation is 12%. Thus is likely sufficient to prevent unwanted modal coupling.

The rectangular cut produces a front to back response ratio of 4.3, while the trapezoidal cut produces a ratio of 4 and the quarter circle produces a ratio of 3.7. However, the location of the nodal plane in the transducers created by sweeping rectangular and trapezoidal cuts is not preferred because it lies in the ceramic itself. The quarter circle cut offers a better node plane position at the back of the front mass and, therefore, it is selected for fabrication.

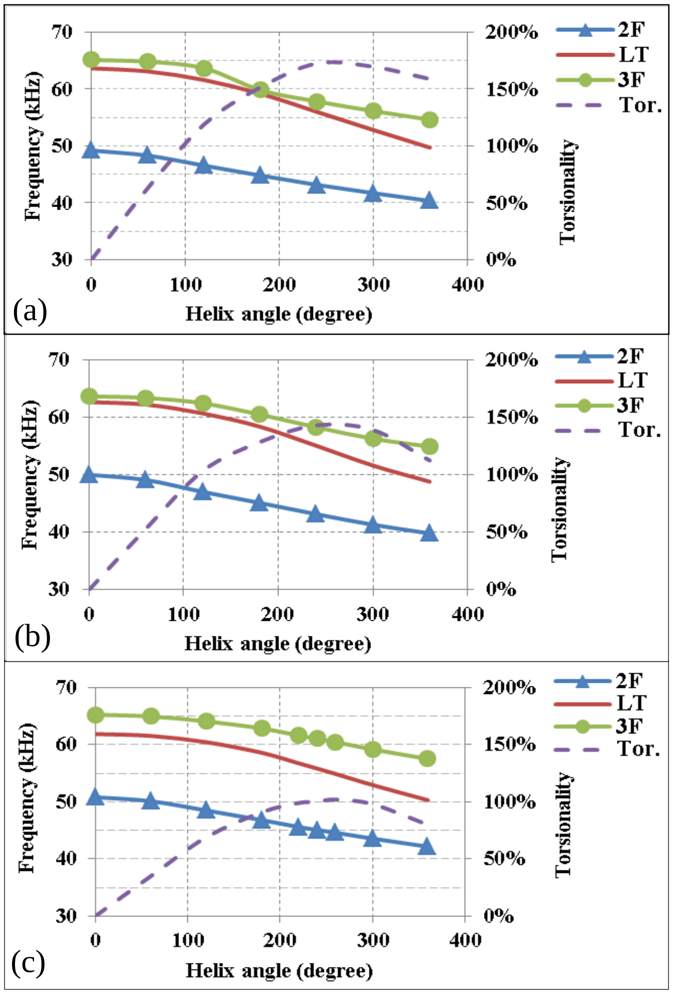

Figure 4. Frequency separation between modes and torsionality of (a) rectangular, (b) trapezoidal and (c) quarter of circle cuts. 2F and 3F refer to the second and third flexural modes, respectively.

III. EXPERIMENTAL ANALYSIS

The fabricated transducer is shown in Fig. 5 where the front mass is modified to create a securing flange at the nodal plane through which the transducer is secured inside a PVC housing. The transducer is tested by an Agilent 4294A impedance analyser to extract the electrical impedance spectrum, including the resonant and anti-resonance frequency of the LT mode, some surrounding modes of vibration, and the electromechanical coupling coefficient. The results are presented in Fig. 6, where the operating LT mode at 55.3 kHz has good frequency separation from the T mode at 44.6 kHz. This result agrees with the FE prediction where the T mode and LT mode resonate at 42.6 kHz and 55.3 kHz, respectively. However, the predicted surrounding F modes are not shown in the extracted impedance spectrum and therefore a further investigation is required to extract the frequency spacing between these modes. Finally the coupling coefficient of the mechanical to electrical energy in the transducer is found to be 0.2.

The experimental modal analysis (EMA) is carried out by using 3D laser Doppler vibrometry to extract the mode shapes of the desired and surrounding modes. A set of 48 points are chosen along the axial direction and the relative responses to a broadband excitation signal are measured. The results are passed to analysis and visualisation software, ME'scopeVES, to extract a wire frame animation of the mode shapes of these modes as shown in Fig. 7. The operating mode at 55.3 kHz has a good frequency separation from the surrounding F modes, at 11.3% and 19.5% respectively. The torsionality can be extracted by dividing the amplitude in T by the amplitude in L at a point on the output surface. The result is found to be 100%, but this is only an indication as the torsionality value should be checked at a higher narrowband excitation level using harmonic analysis. Finally the minimum vibration is located at the securing flange which also matches the FE prediction.

The 3D vibrometry equipment is used for the harmonic analysis, where different levels of sinusoidal burst excitation are applied and the responses, in axial and tangential directions, of a circumferential point of the output surface are measured. This test is carried out for unloaded (free) and loaded (clamped) transducer conditions where a load of 7 N is applied axially to the output surface. The responses are presented in Fig. 8 where, although the applied load decreases both L and T responses, it improves the torsionality by damping the L response more than the T response when the torsionality reaches 100%. Also it can be seen that the torsionality is almost constant over this range of excitations, as shown in Fig. 9, which is considered to be another advantage of this technique.

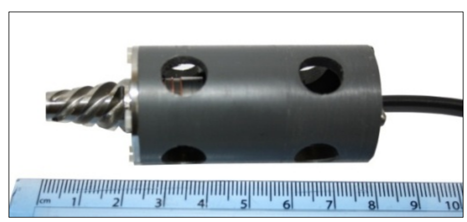

Figure 5. Fabricated transducer.

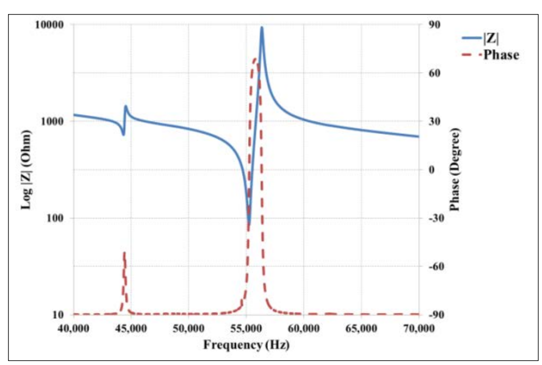

Figure 6. Impedance spectrum and phase diagram of the transducer.

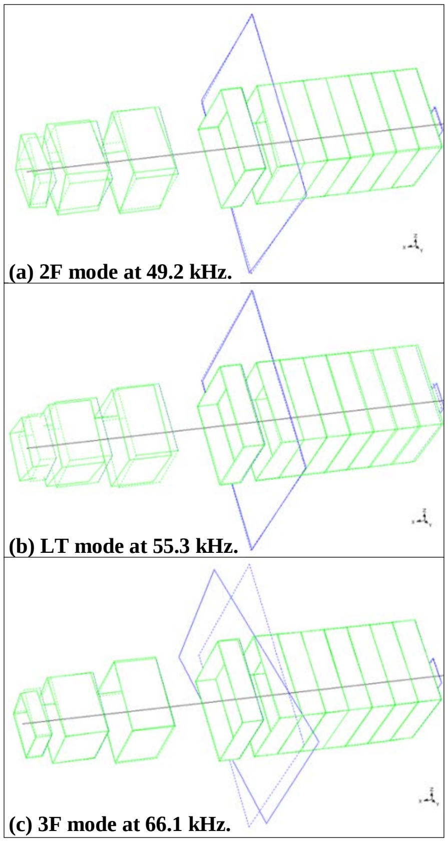

Figure 7. Mode shape of (a) 2F mode, (b) LT mode, and (c) 3F mode of vibration.

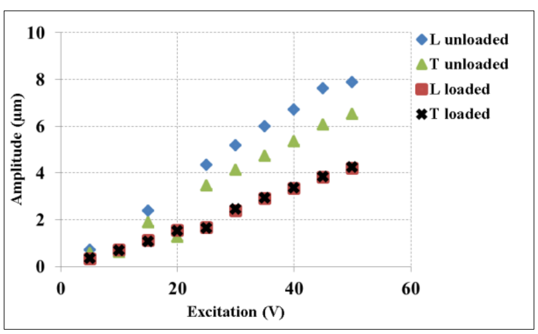

Figure 8. Amplitude (pk-pk) of unloaded and loaded transducer.

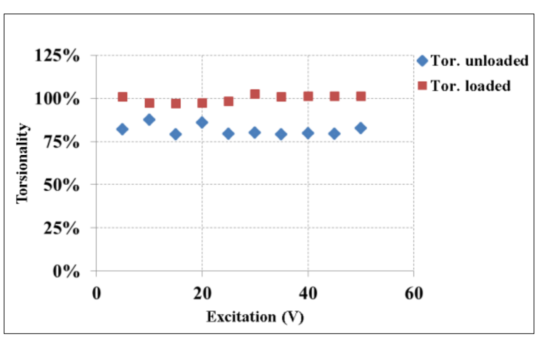

Figure 9. Torsionality of unloaded and loaded transducer.

IV. Conclusion

Degeneration of the longitudinal mode into longitudinal-torsional vibration can be achieved and optimised to suit various ultrasonic applications. A slotted exponential waveguide can be used to improve the response and the cross-section and helix angle of the slots have been shown to be effective parameters through which the vibration behaviour of the horn may be controlled.

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