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Design of Miniature Ultrasonic Surgical Devices

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Abstract — **Orthopaedic surgery involves cutting through bone and the removal of bone, bone spurs or ligament. Ultrasonic surgical devices, employing an ultrasonically excited cutting blade, have demonstrated precision and accuracy in bone surgeries, allowing surgeons to carry out bone cutting in difficult-to-reach surgical sites. For surgical procedures in a confined space, a small surgical device has benefits, but for ultrasonic devices this results in a reduced amount of piezoceramic material in the transducer. This paper provides insights into the trade-offs between the volume of piezoceramic material, location of the piezoceramic rings, resonant frequency and the achievable vibration amplitude. Bolted Langevin-style Transducers (BLT) are adopted for this study. Experimental results show that a similar level of vibration displacement can be achieved at a much lower input voltage with a higher quantity of piezoceramic elements. However, the associated nonlinear behaviour is exacerbated. Locating the piezoceramic elements at the longitudinal displacement node is critical, in order to maximise the ultrasonic energy transfer.**

Keywords—Ultrasonic surgical device, BLT transducer

I. Introduction

Ultrasonic surgical devices provide excellent hemostasis, efficient transection, minimal lateral thermal damage, low smoke generation, and no risk of electrical current passage to patient [1], due to the inherent characteristics of the ultrasonic cutting mechanism. For bone cutting, the introduction of ultrasonically excited devices can be traced back to the early 1950s for dentistry applications [2].

The Piezosurgery® device, which was commercialised in the late 1980s, was first used by oral and maxillofacial surgeons for osteotomy, but nowadays this technology has been applied in neurosurgery and orthopaedic surgeries [3]. For laparoscopic surgeries, Ethicon released a commercial hand-held ulrasonic scalpel device, which has been applied extensively in human patients. The original version was the Harmonic Ace® [4] whose operating frequency is around 55 kHz. For brain surgeries, ultrasonic aspiration devices are commonly used for resecting intracranial tumours [5] and the existing models include CUSA Integra®, Söring® and Stryker Sonopet®. These devices use low frequency ultrasound to emulsify and fragment tissue while simultaneously irrigating and aspirating the surgical field.

Although there have been many innovations and performance advancements of the ultrasonic surgical devices in clinical use, their physical size remains an issue for adoption in many minimally invasive surgeries. Therefore, there is a need for miniature ultrasonic surgical cutting devices which can be guided and manoeuvred to more difficult-to-reach surgical sites minimally invasively through small access routes.

The targets for the device set for this study is a diameter of 8 mm, a length of 50 mm and a vibration amplitude at the cutting tool tip of at least 30 μm peak-to-peak, and preferably much higher, to facilitate effective tissue cutting.

II. Transducer Design and Fabrication

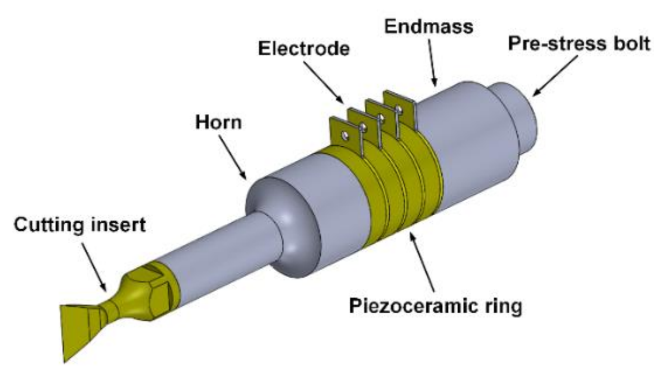

Fig. 1. Structure of a BLT surgical cutting tool

The structure of a Bolted Langevin-style Transducer (BLT) surgical cutting tool, as an example of a bone surgery device, is shown in Fig. 1. The device converts electrical energy into mechanical vibrations via four piezoceramic rings, an end mass, a horn, a cutting insert and a pre-stress bolt. The horn has a tapered profile to amplify the oscillation amplitude at the cutting tip developed by the piezoceramic rings. The piezoceramic rings, end mass and horn are clamped by means of a pre-stress bolt, thus forming the sandwich configuration.

Ultrasonic surgical devices are generally operated at a low ultrasonic frequency, typically in the 20 kHz to 100 kHz range [6], and available vibration amplitude tends to be lower at higher resonant frequencies. If a BLT transducer has a solid cylindrical structure, the resonant frequency is approximately equal to the velocity of sound in the transducer metal material divided by the wavelength. Therefore, for a cutting device of length 50 mm operating as a half or full wavelength, the resonant frequencies are around 50 kHz and 100 kHz respectively for a titanium alloy Ti6Al4V transducer.

In order to investigate the vibrational response of ultrasonic

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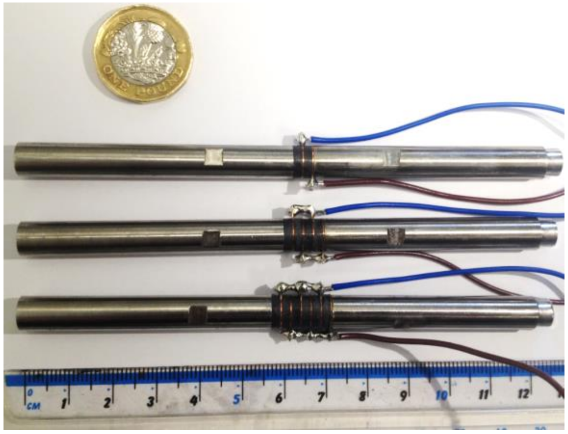

Fig. 2. 2-ring, 4-ring and 6-ring cylindrical transducers

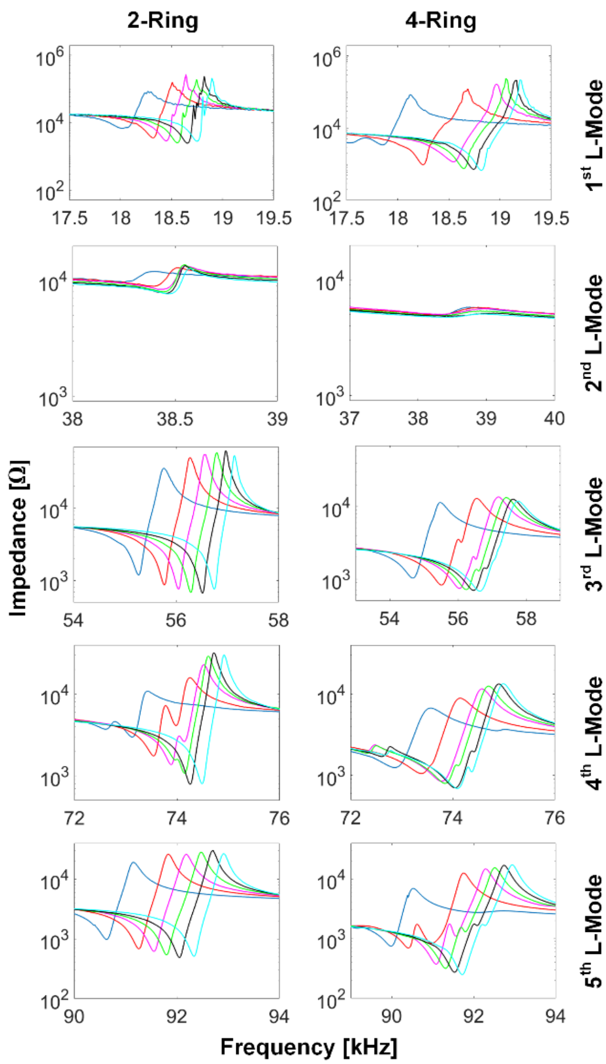

Fig. 3. Impedance of 2-ring and 4-ring transducers: - 0.5 Nm, - 1.0 Nm, - 1.5 Nm, - 2.0 Nm, - 2.5 Nm, - 3.0 Nm

transducers across the 20 kHz to 100 kHz range at elevated power levels, three cylindrical BLT transducers with an 8 mm diameter and a 125 mm length with two, four and six piezoceramic rings, were designed using FEA (Abaqus-Simulia, Dasault Systèmes) and are presented in Fig. 2. These devices are all longitudinal-mode half-wavelength at around 20 kHz, but can also be excited at higher harmonic frequencies, namely 40kHz, 60kHz, 80kHz and 100kHz. Considering the length of the target miniature device is no more than 50mm, and if the device is operated at the half wavelength regime, its vibration amplitude will be almost equal to the output of the long and cylindrical devices driven at the 3rd longitudinal modes at around 60kHz.

III. RESULTS

A. Impedance

During fabrication, transducers were pre-stressed to compensate for the low tensile strength of the piezoceramic elements [7], while ensuring the applied pre-stress was not excessive as this will result in piezoceramic pronounces depoling, with unstable impedance and ageing [8]. The resulting torque used was 3.0 Nm, providing a pre-stress in the acceptable region of 15 MPa to 30 MPa [9] and avoiding overtightening.

Results of the measured impedance for the 2-ring and 4-ring transducers are shown in Fig. 3. The figure shows the trend in the change of resonant frequency and impedance for the first five longitudinal modes as the applied torque increases. Both resonant and anti-resonant frequencies increase, but the electrical impedance decreases. However, the rate reduces as the torque approaches delivery of the recommended pre-stress, which means an electrical stability is reached.

B. Modeshapes

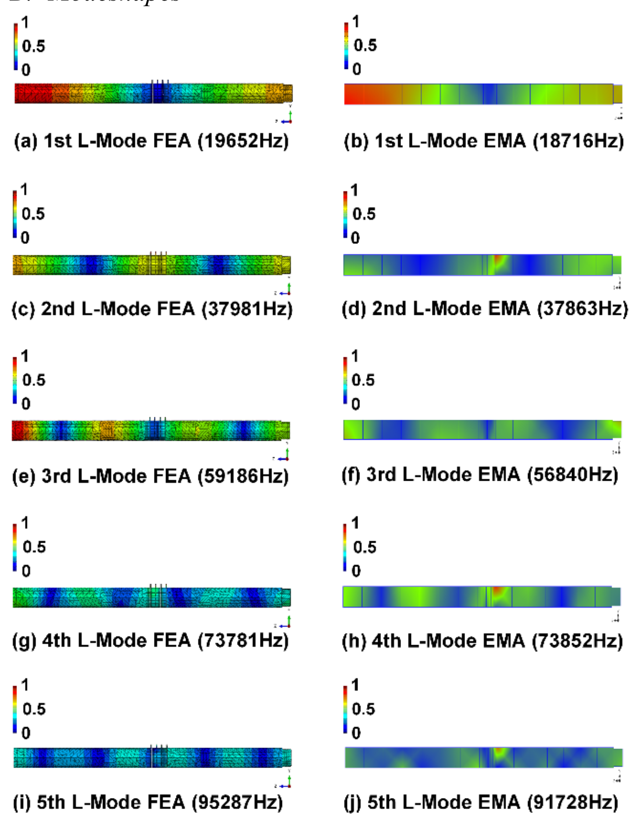

Fig. 4. FEA vs EMA of the 4-ring cylindrical transducer

Experimental Modal Analysis (EMA) was performed to measure the vibrational mode shapes and modal frequencies of the transducers. As an example, the first five longitudinal mode shapes obtained from FEA simulation and experiments for the 4-ring transducer are presented in Fig. 4. The predicted mode shapes from the FEA are readily matched with mode shapes extracted from the experimentally measured data. It should be noted that when the transducers are excited in their 2nd and 4th longitudinal modes, the locations of the piezoceramic rings are at a longitudinal anti-node, which is an unconventional location of piezoceramics , which needs to be close to a node [10].

C. Vibrational Response

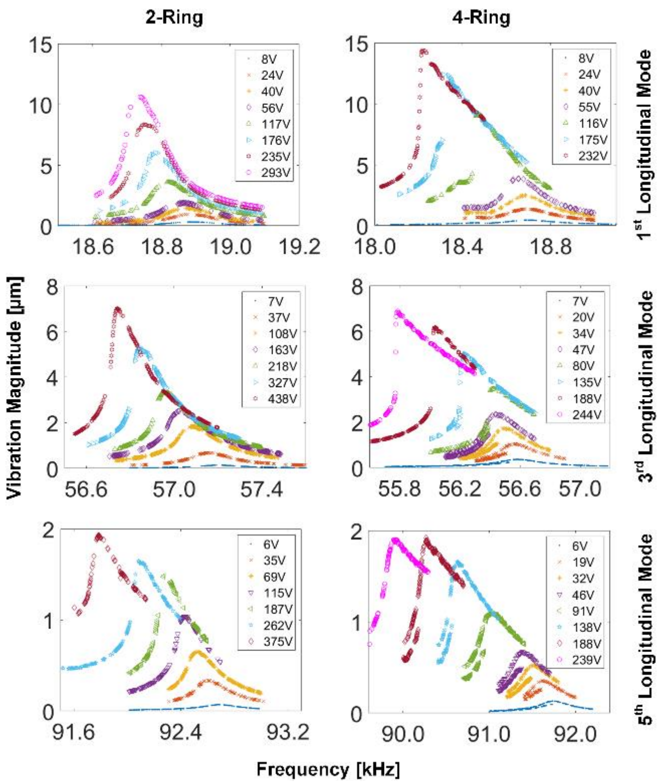

Fig. 5. Vibration at 1st, 3rd and 5th longitudinal modes with 2 and 4 rings

To study the vibrational response of the transducers at increasing excitation levels, harmonic characterisation experiments were performed. The transducers were excited through resonance via a frequency sweep of the excitation signal at incrementally increasing excitation levels. The vibration displacement of the transducer output face was measured with a 1-D laser Doppler vibrometer.

Fig. 5 shows the vibrational responses of the 2-ring and 4-ring transducers excited at the 1st, 3rd and 5th longitudinal modes, which means the piezoceramic rings are located at a displacement node according to the experimentally extracted mode shapes in Fig. 4. This is commonly known as a 'resonant tuning' regime [11]. To predict the vibrational response of the miniature transducers, the outputs of the long cylindrical transducers driven at the 3rd longitudinal mode is of interest.

Fig. 5 shows how the vibration amplitude increases with applied voltage, but the achievable vibration amplitude is significantly reduced when driving at the 3rd then 5th longitudinal mode for the same input voltage. The result is that transducers with a double volume of piezoceramic elements present an almost twice high vibration amplitude using a same level of excitation voltage. In the 1st longitudinal mode, at around 19 kHz, the 4-ring device excites a 15 μm vibration amplitude and the vibration amplitude is 11 μm for the 2-ring device. Driven at the 3rd longitudinal mode, at around 57 kHz, both 2-ring and 4-ring devices excite a 7 μm amplitude and this drops to below 2 μm when the devices are excited in the 5th longitudinal mode, at around 92 kHz.

Another observation is that the response curves are linear and symmetric at low excitation levels, but the resonant frequency reduces, and the response curves lose their symmetry and bend to the left at higher excitation levels. This is commonly referred to as stiffness softening and exhibits as backbone curves, typical of nonlinear dynamic systems [12]. At the highest excitation levels, the nonlinearity additionally features a sudden jump in the response level as the frequency is swept through resonance, exhibiting as a strongly asymmetric feature, again typical of the jump phenomenon in nonlinear dynamic systems (such as Duffing oscillators) [13].

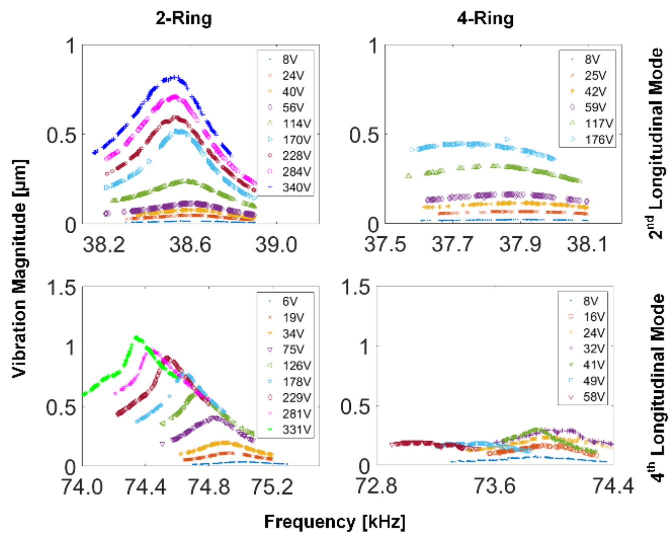

Fig. 6. Vibration at 2nd and 4th longitudinal modes with 2 and 4 rings

Fig. 6 presents the results of driving the transducers at the 2nd and 4th longitudinal modes, where the piezoceramic rings are located at a displacement anti-node. The vibration displacement achieved in this configuration is very low, not exceeding 1 μm even at the highest excitation level.

IV. CONCLUSION

This paper describes initial research into the trade-offs between the volume of piezoceramic material, location of the piezoceramic discs, resonant frequency and the achievable vibration amplitude of three long cylindrical BLT transducers.

Experimental results show that the transducers with a double volume of piezoceramic elements presents an almost twice high vibration amplitude using a same level of excitation voltage, as a result of the increased capacity of power handling in the devices. Nonetheless, the nonlinear behaviour is worsened, especially for the higher frequency longitudinal modes. It is shown that it is crucial to locate the piezoceramic elements at the longitudinal node, otherwise the achievable vibration amplitude is very low. For the prediction of the vibration of the miniature ultrasonic transducers, the tip can easily deliver an over 30 μm peak-to-peak amplitude if a tapered horn is employed, which is concluded from the experimental results of the long cylindrical transducers at the 3rd longitudinal mode.

REFERENCES

[1] D. Broughton, A. L. Welling, E. H. Monroe, K. Pirozzi, J. B. Schulte, and J. W. Clymer, "Tissue effects in vessel sealing and transection from an ultrasonic device with more intelligent control of energy delivery," *Medical Devices: Evidence Research*, Vol. 6, pp. 151-154, 2013

[2] M. Catuna, "Sonic energy: a possible dental application," *Annual Dentistry*, vol. 12, pp. 100-101, 1953.

[3] M. Labanca, F. Azzola, R. Vinci, and L. F. Rodella, "Piezoelectric surgery: Twenty years of use," *British Journal of Oral and* Maxillofacial *Surgery*, vol. 46, no. 4, pp. 265-269, 2008.

[4] D. G. Nicastri, M. Wu, J. Yun, and S. J. Swanson, "Evaluation of efficacy of an ultrasonic scalpel for pulmonary vascular ligation in an animal model," *The Journal of Thoracic Cardiovascular Surgery*, vol. 134, no. 1, pp. 160-164, 2007.

[5] S. Henzi, N. Krayenbühl, O. Bozinov, L. Regli, and M. N. Stienen, "Ultrasonic aspiration in neurosurgery : comparative analysis of complications and outcome for three commonly used models," *Neurosurgical technique evalution*, 2019.

[6] M. Lucas, A. Gachagan, and A. Cardoni, "Research applications and opportunities in power ultrasonics," *Proceedings of the Institution of Mechanical Engineers*, *Part C: Journal of Mechanical Engineering Science*, vol. 223, pp. 2949-2965, 2009.

[7] E. Riera, A. Cardoni, A. Blanco, V. Acosta, and J. Gallego-Juárez, "Characterising the nonlinear dynamics of power ultrasonic systems," *Internoise 2010, noise and sustainability*, no. 43, pp. 1-10, 2012.

[8] D. A. DeAngelis, G. W. Schulze, and K. S. Wong, "Optimizing piezoelectric stack preload bolts in ultrasonic transducers," *Physics Procedia*, *43rd Annual Symposium of the Ultrasonic Industry Association,* vol. 63, pp. 11-20, 2015.

[9] C. K. Fung, "Ultrasonic Transducer Equipped with a Magnetoelectric Sensor for Weld Quality Monitoring, " *The Hong Kong Polytechnic University, Master Theses*, March, 2009.

[10] S. Lin, "Optimization of the performance of the sandwich piezoelectric ultrasonic transducer," *The Journal of the Acoustical Society of America*, vol. 115, no. 1, pp. 182-186, 2004.

[11] V. K. Astashev and K. A. Pichygin, "Resonance adjustment and optimization of parameters of an ultrasonic rod system with a piezoelectric vibration exciter," *Journal of Machinery Manufacture and Reliability*, vol. 42, no. 5, pp. 347-352, 2013.

[12] V. Agarwal, X. Zheng, and B. Balachandran, "Influence of noise on frequency responses of softening Duffing oscillators," *Physics Letters A,* vol. 382, no. 46, pp. 3355-3364, 2018.

[13] B. Ducharne, D. Guyomar, G. Sebald, and B. Zhang, "Modeling energy losses in power ultrasound transducers," *Power Ultrasonics,* pp. 241-256, 2015.