Available online at www.sciencedirect.com

ScienceDirect

Physics Procedia 70 (2015) 10 – 13

Physics Procedia

2015 International Congress on Ultrasonics, 2015 ICU Metz

Design of a slender tuned ultrasonic needle for bone penetration

Rebecca Cleary[a], Andrew Mathieson[a], Robert Wallace[b], Hamish Simpson[b], Margaret Lucas[a]*

[a]*School of Engineering, University of Glasgow, Glasgow, G12 8QQ, UK*
[b]*School of Clinical Sciences, University of Edinburgh, Edinburgh, EH8 9YL, UK*

Abstract

This paper reports on an ultrasonic bone biopsy needle, particularly focusing on design guidelines applicable for any slender tuned ultrasonic device component. Ultrasonic surgical devices are routinely used to cut a range of biological tissues, such as bone. However the realisation of an ultrasonic bone biopsy needle is particularly challenging. This is due to the requirement to generate sufficient vibrational amplitude capable of penetrating mineralised tissue, while avoiding flexural vibrational responses, which are known to reduce the performance and reliability of slender ultrasonic devices. This investigation uses finite element analysis (FEA) to predict the vibrational behaviour of a resonant needle which has dimensions that match closely to an 8Gx4inch bone marrow biopsy needle. Features of the needle, including changes in material and repeated changes in diameter, have been included and systematically altered to demonstrate that the location of and geometry of these features can significantly affect the resonant frequency of bending and torsional modes of vibration while having a limited effect on the frequency and shape of the tuned longitudinal mode. Experimental modal analysis was used to identify the modal parameters of the selected needle design, validating the FEA model predictions of the longitudinal mode and the close flexural modes. This verifies that modal coupling can be avoided by judicious small geometry modifications. Finally, the tuned needle assembly was driven under typical operational excitation conditions to demonstrate that an ultrasonic biopsy needle can be designed to operate in a purely longitudinal motion.

Peer-review under responsibility of the Scientific Committee of ICU 2015

Keywords: Ultrasonic Needle; FEA; EMA; bone biopsy

* Corresponding author. Tel.: +44-141-330-4323.
E-mail address: Margaret.Lucas@glasgow.ac.uk

Peer-review under responsibility of the Scientific Committee of ICU 2015
doi:10.1016/j.phpro.2015.08.005

1. Introduction

Developments in high power ultrasonic technology for clinical applications have resulted in surgical devices offering greater precision even in delicate procedures. Interest in ultrasonic bone cutting has grown since it was first introduced commercially as Piezosurgery (Eggers (2004), Labanca (2008)). More recent studies (Grauvogel (2013)) have focused on precision cutting of bone reducing the risk of damage to surrounding delicate tissues, in comparison with manual and other powered instruments.

This study investigates the design of an ultrasonic needle capable of penetrating through bone, for bone biopsies. The aim is to penetrate bone with considerably less force that a conventional bone biopsy, with a more controlled penetration, removing the need for twisting of the needle. The benefits that could result are an improvement in the quality of the retrieved specimen, a more precise biopsy procedure, and reduced patient discomfort.

The ultrasonic needle is driven by a Langevin transducer. The needle is designed to vibrate in a pure longitudinal mode but, since it is a slender geometry, there is significant risk of a dense spectral response around the operating frequency with bending and torsional modes excited at very close natural frequencies to the tuned frequency. It is therefore important to investigate how adequate modal frequency spacing can be achieved through FE modelling and validate the modelling results through needle testing.

2. Finite Element Analysis

Abaqus, a finite element analysis (FEA) package, was used to develop a model of the ultrasonic needle device, consisting of a Langevin transducer, composed of piezoceramic discs (Sonox P8), copper electrodes, titanium front and back masses and a steel pre-stress bolt, attached to a needle insert made from surgical stainless steel 316LVM. The insert was in the form of a long slender tube.

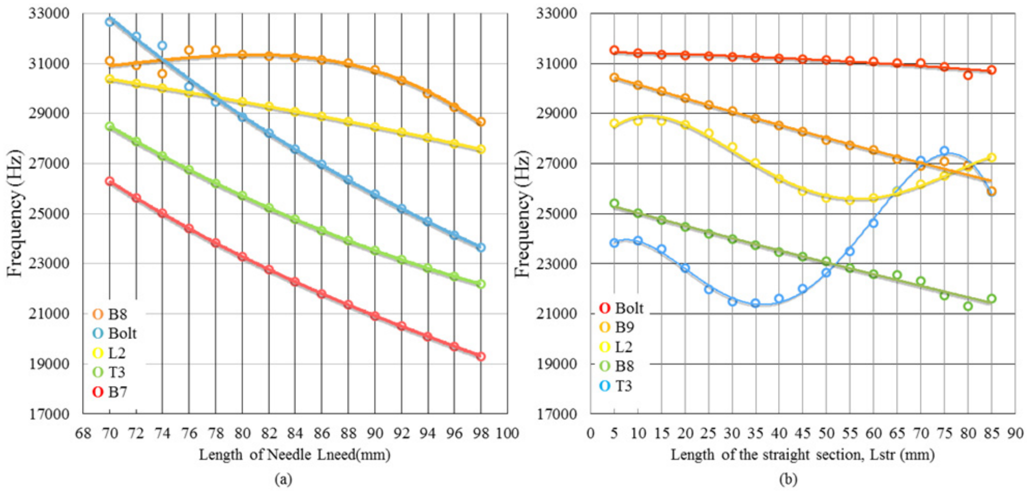


Fig. 1. FEA predicted modal frequencies as (a) length of the needle insert, Lneed altered; (b) length of the straight section, Lstr altered.

Initially a conical needle insert was adopted and the length, L_{need}, was altered, executing an eigenmode extraction to calculate the mode shapes and modal frequencies. The ultrasonic needle device was tuned to the 2nd longitudinal mode, L2. Fig. 1(a) shows the predicted natural frequencies as the length of the needle insert increases from 68mm to 98mm. A length of 90 mm provided the best frequency spacing around the L2 mode, giving a predicted tuned frequency of 28.5 kHz for the full wavelength device. The two closest neighbouring modes of vibration are a bolt bending mode and the 8th bending mode of the needle, which are frequency separated by 8% and 9% respectively. Often modes associated with the pre-stress bolt are ignored in the design of ultrasonic devices and these results demonstrate the need to characterise them, especially for slender devices.

The next stage of the investigation was the introduction of a cylindrical length of the tubing, of constant outer and inner radii, to form the narrow slender section suitable for insertion in bone. The length of the straight cylindrical section, L_{str}, was varied in the FE model while keeping the total length of the insert constant at 90 mm. The eigenmode extraction procedure was once again performed and the calculated frequencies are shown in Fig. 1(b). The length of straight section which resulted in the highest frequency spacing between L2 and the neighbouring modal frequencies was 45 mm, where the separations from the 8^{th} and 9^{th} bending mode were 10% and 9% respectively. The final design of the transducer including the needle insert, illustrated in Fig. 2, was consequently tuned at 25.9 kHz.

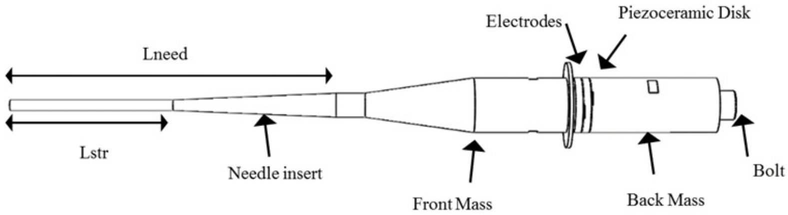


Fig. 2. Ultrasonic needle device

3. Experimental Modal Analysis

EMA was performed by exciting the ultrasonic needle device with a random excitation over the frequency range 0-50 kHz and measuring the vibration response using a 3D laser Doppler vibrometer (LDV), (Polytec, CLV-3D), across a grid of points on the surface of the device. The transducer was excited by a signal generator/analyser (Data Physics Quattro DP240) and the excitation signal was then amplified by a power amplifier (QSC RMX). Frequency response functions were measured at each grid point and curve-fitted using ME'Scope modal analysis software. The magnitude and phase data was applied to a geometric model of the measurement grid, allowing animated mode shapes to be derived at each modal frequency.

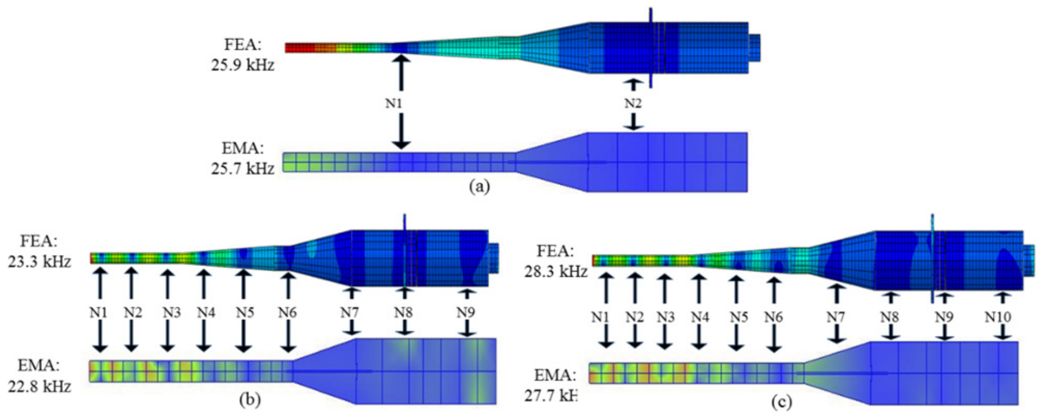


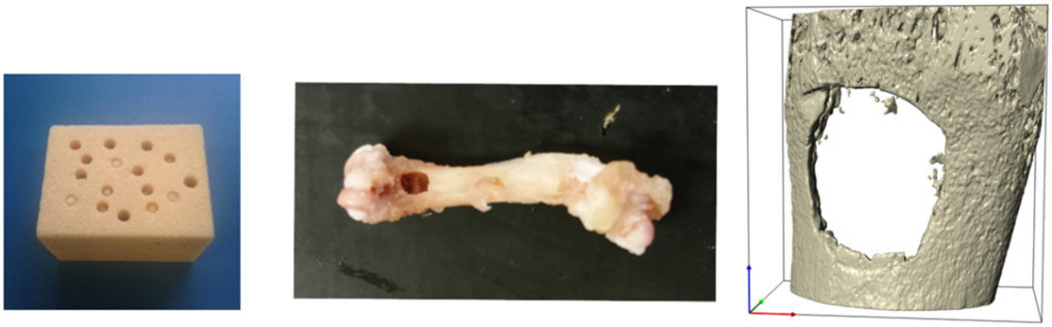
Fig.

3: FEA and EMA, (a) L2, (b) B8 (c) B9

The results show the L2 mode at 25.7 kHz whilst the closest bending modes B8 and B9 were at 22.8 kHz and 27.7 kHz respectively, giving frequency spacing of 11% and 8%. The modes can be identified and compared with the FEA results by the nodal positions. The three mode shapes from EMA and the corresponding FEA results are shown in Fig. 3. The nodes are depicted in blue and the antinodes are depicted in green for bending modes and red for the longitudinal mode. A difference between FEA estimated and EMA measured frequencies for both the bending modes, B8 and B9, was 2.1% while the difference for L2 was 0.8%.

4. Needle penetration testing

Penetration tests were carried out to investigate the performance of the final needle design, the 90 mm needle insert with a 45 mm straight cylindrical length. The device was excited by a resonance tracking and vibration stabilisation system (Kuang (2014)). During the test a biomedical bone mimic (Sawbones, a polyurethane foam which offers similar mechanical properties to bone) was penetrated. A smooth penetration through the mimic to a 50 mm depth was achieved, shown in Fig. 4(a), with very low force required and no signs of burning. The next stage of testing was to drive the needle into a femur bone from a 3 month Wistar rat, Figure 4(b). A Skycan 1172 Micro-CT, scanning at a resolution of 3 µm per voxel, was used to characterise the mechanical damage. The micro-CT, Figure 4(c), revealed a small amount of micro-damage around the hole but no large cracks, suggesting that the device can penetrate through cortical bone without inducing severe mechanical damage.



(a) (b) (c)

Fig. 4 Penetration through (a) polyurethane foam, (b) femur bone, and (c) a micro-CT image of the Wistar rat femur

5. Conclusion

The design of a novel ultrasonic needle device was presented, using FEA to identify a geometry for adequate modal frequency spacing. EMA validated the FEA results, allowing the device, operating in a pure longitudinal mode without coupling with parasitic flexural motion normally associated with slender devices, to be tested on a biomechanical bone mimic material and rat bone. The penetration tests resulted in minimal micro-damage at the penetration site.

Acknowledgements

This work was funded by the Engineering and Physical Sciences Research Council (EPSRC) EP/K020013/1, with project partner Ethicon Inc.

References

Eggers, G., Klein, J., Blank, J., Hassfeld, S., 2004, Piezosurgery®: An ultrasound device for cutting bone and its use and limitations in maxillofacial surgery Br J Oral Maxillofac Surg; 42(5):451-3

Grauvogel, J., Scheiwe, C., Kaminsky, J., 2013, Use of Piezosurgery for removal of retrovertebral body osteophytes in anterior cervical discectomy, Spine J. 14(4):628-36

Kuang,Y., Jin, Y., Cochran, S., Huang, Z., 2014, Resonance tracking and vibration stablilization for high power ultrasonic transducers. Ultrasonics. 54(1):187-94

Labanca, M., Azzola, F., Raffaele, V., Rode, L.F., 2008, Piezoelectric surgery: Twenty years of use, Br J Oral Maxillofac Surg; 46(4):265-9