Resonance Frequency Stability of a Nitinol Class IV Flextensional Transducer

G.J. Puthenvila, M. Hafezi, A. Feeney, and M. Lucas[a]

Centre for Medical and Industrial Ultrasonics, James Watt School of Engineering, University of Glasgow,
Glasgow, G12 8QQ, United Kingdom.

[a]Margaret.Lucas@glasgow.ac.uk

Abstract Flextensional transducers together comprise several configurations of electroacoustic device which have been popular for several decades in underwater applications such as sonar. In recent years, the modification of one of these classes, the cymbal, has been the subject of research for power ultrasonics applications including surgical cutting, and for adaptive frequency transducers using Nitinol as the end-cap material. Nitinol can switch between two phase microstructures with dissimilar Young's moduli, allowing resonance tuneability of a device fabricated using it. However, it is known that the class IV flextensional has the potential to deliver enhanced vibration amplitudes per unit volume of piezoelectric material in the configuration, compared to the class V cymbal. In this study, the design, fabrication, and characterisation of a Nitinol class IV transducer is reported, and compared with a stainless steel equivalent. Resonance frequency stability is demonstrated via electrical impedance analysis, within a typical temperature range associated with ultrasonic transducers under load. This is important because a temperature increase generally results in a reduction in resonance frequency in ultrasonic transducers, but an increase would be expected for a Nitinol transducer going through a phase transformation.

Introduction The traditional class IV flextensional transducer comprises a piezoelectric ceramic bar, the length mode of which drives vibrations of a metallic shell producing a flexural motion with relatively high displacement amplitude. The class IV transducer has been predominantly used in low frequency underwater applications [1]. In recent years, there has been some exploration of the transducer's potential for power ultrasonic applications such as ultrasonic surgery [2]. In general, there has been renewed focus on flextensional transducers in recent years for power ultrasonics. For example, the class V cymbal has been investigated for ultrasonic surgical prototypes [3], and adaptive frequency configurations have been proposed which incorporate the shape memory alloy Nitinol [4]. The advantage of using a material such as Nitinol is that an ultrasonic device can be engineered to switch resonance frequencies via the microstructural phase transformation in the material. This may have the potential to improve ultrasonic surgery outcomes, for example to optimise the cutting of soft and hard tissues using one device. Although progress has been made with the class V cymbal, it has been reported that enhanced vibration performance can be achieved through the class IV, when compared per unit volume of piezoelectric material in the configuration [2]. The aim of this study is to introduce Nitinol into the class IV transducer, thus exploring associated design and fabrication challenges.Nitinol experiences phase transformations between the highly symmetric, stiffer cubic austenite phase at (relatively) high temperatures and the less ordered, more compliant martensite phase at comparatively low temperatures. The Young's modulus of martensite typically varies between 28-41 GPa, whereas austenite has a Young's modulus of 60-90 GPa [5]. Given the differences in Young's modulus, the aim of the study is to demonstrate a Nitinol class IV transducer, for example for adaptive or tuneable resonance frequency. It is known that Nitinol can be difficult to machine, and so the challenges associated with fabricating a Nitinol class IV transducer are also investigated here, where a prototype is manufactured and then characterised using electrical impedance analysis. The resonance frequency of the Nitinol class IV is compared to one made using stainless steel end-caps, to illustrate the influence of temperature on both configurations.

Transducer Fabrication and Characterisation Nitinol end-caps were manufactured from sheets (Kellogg's Research Labs, NH, USA), with a nominal austenitic final transformation temperature of 35°C. Since this is above ambient room temperature, the Nitinol end-caps should be able to switch from more compliant martensite to the austenite microstructure with a relatively modest rise in device temperature. A class IV transducer was designed using Abaqus FEA (Dassault Systémes, France), at first using realistic estimates for the Young's moduli, from literature and manufacturer sources [5]. Another class IV transducer was also designed using stainless steel, and both transducers were tuned to a resonance frequency between 20 kHz and 30 kHz at room temperature. The transducers were then fabricated, where the Nitinol end-caps were manufactured using electrical discharge machining. The end-caps were bonded to the piezoelectric ceramic bar using epoxy resin (Eccobond 45LV High Strength, Ellsworth Adhesives Ltd., UK). The fabricated Nitinol class IV transducer is shown in Fig. 1.

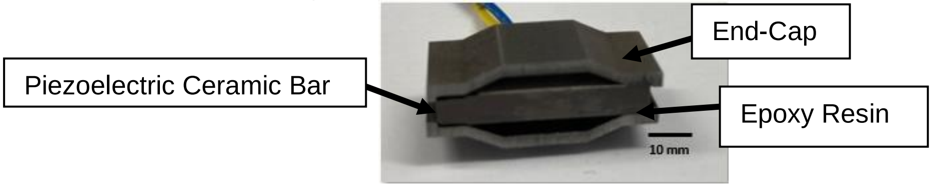

Fig. 1: The Class IV flextensional transducer with Nitinol end-caps.

The series resonance frequencies of both transducers were then measured as a function of temperature towards 70°C, using an electrical impedance analyser (4294A, Keysight Technologies,CA,USA). A commercial dehydrator (Andrew James, UK) was used to control the temperatures of the transducers, where they were permitted to thermally equilibriate for around 5 min at each temperature before a measurement was taken. The series resonance frequencies as functions of temperature are shown in Fig. 2.

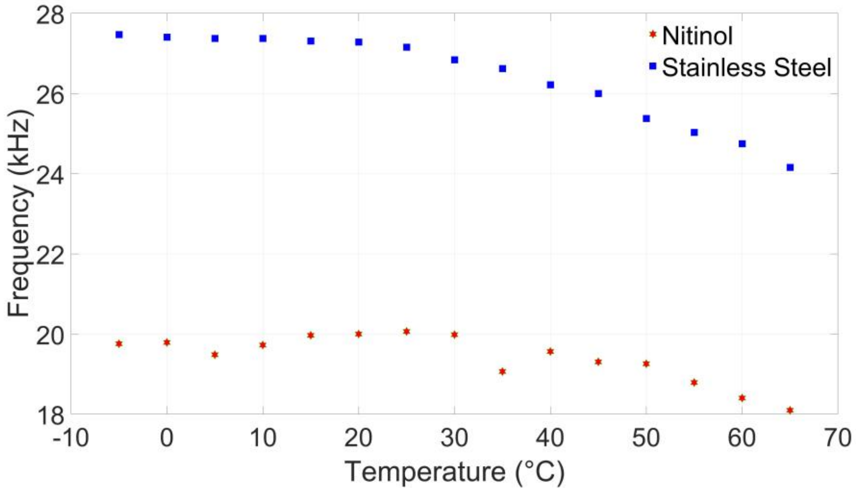

Fig. 2: Series resonance frequencies as functions of temperature for the prototype transducers.

The results show an unexpected trend for the Nitinol class IV transducer. The austenitic transformation temperature is higher than ambient room temperature by at least 10°C, thus it would be expected that the resonance frequency of the transducer would increase, consistent with observations from the literature on the class V cymbal [6]. However, a relatively steady resonance frequency has been measured with increasing temperature, one reason being that the Nitinol is in a superelastic phase, indicating that the final austenitic transformation temperature has already been passed. It is likely that the required machining of the end-caps has influenced the transformation temperatures of the material, through the introduction of residual stresses, thus reducing the threshold for the transition to austenite. There is a more stable resonance frequency with temperature for the Nitinol transducer, across the measured temperature range, demonstrating a novel and potentially impactful outcome for the integration of Nitinol in this configuration. There may also be competing influences on the transducer dynamics as temperature rises, where piezoelectric ceramic elements are generally known to soften, whereas Nitinol stiffens. This may explain, in part, the difference in the data trend for the two transducer prototypes. Future studies can focus on engineering Nitinol class IV transducers with higher austenitic transformation temperatures, investigating the influences of end-cap fabrication on Nitinol transformation characteristics the transformation characteristics, and to further study dynamic stability.

Conclusion In this study, two class IV transducers were designed and fabricated; Some of the challenges of ultrasonic transducer fabrication using Nitinol include the influence of machining which can cause residual stresses that influence transformation behaviour. An expected increase in resonance frequency was not measured for the Nitinol transducer, likely due to the influence of machining on the Nitinol transformation temperatures. Nevertheless, a more stable resonance frequency with increasing temperature is measured for the Nitinol class IV transducer compared to the stainless steel, up to 70°C.

References

[1] A. Feeney, A. Tweedie, A. Mathieson and M.Lucas: *A Miniaturized Class IV Flextensional Ultrasonic Transducer*, Physics Procedia, 87 (2016), pp. 10–15.

[2] A.Mathieson, A.Cardoni, N.Cerisola and M.Lucas: *Understanding Nonlinear Vibration Behaviours in High-Power Ultrasonic Surgical Devices*, Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences, 471(2176), p. 20140906 (2015).

[3] F.Bejarano, A.Feeney, R.Wallace, H.Simpson and M.Lucas: *An Ultrasonic Orthopaedic Surgical Device Based on a Cymbal Transducer*, Ultrasonics, 72 (2016), pp. 24–33.

[4] A. Feeney and M.Lucas: *Smart Cymbal Transducers With Nitinol End Caps Tunable to Multiple Operating Frequencies*, IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control, 61(10) (2014), pp. 1709–1719.

[5] M.K. Gupta, V.Panwar and R. Prasad Mahapatra: *Temperature and Strain Rate Dependent Stress-Strain Behaviour of Nitinol*, Materials Today: Proceedings, 43 (2021), pp. 395–399.

[6] S.Smith, X.Li, M.Hafezi, P.Barron, M.Lucas and A.Feeney: *Enhanced Resolution Phase Transformations in a Nitinol Cymbal Ultrasonic Device*, IEEE International Ultrasonics Symposium (IUS) (2022).