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Enhanced resolution phase transformations in a Nitinol cymbal ultrasonic device

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***Abstract*—The traditional form of cymbal transducer is composed of cymbal endcaps bonded to a piezoelectric ceramic, whose radial vibrations drive relatively high amplitude endcap displacements. This transducer has been investigated for sonar and energy harvesting, but recent research has focused on adapting it for higher power applications, such as surgical cutting. In such procedures, there are known challenges in the efficient cutting of different materials, such as bone and muscular tissue, using one device. One viable method is to introduce adaptive dynamic properties, including operating frequency, by fabricating the caps with a shape memory alloy. Here, elastic modulus can be tuned by inducing a phase transformation, allowing rapid control of device dynamics. In this study, the temperature-dependent dynamics of a Nitinol cymbal device are examined using electrical impedance analysis and laser Doppler vibrometry, and practical aspects of introducing Nitinol into such devices are considered. The results show that a mixed austenitic and martensitic microstructure creates intermediate stiffnesses and exhibit the potential to administer minor temperature changes to achieve significant resonance shifts.**

Keywords—Nitinol, adaptive ultrasonics, tuneable frequency

I. INTRODUCTION

Ultrasonic devices for high power applications, such as drilling, welding, or bone surgery, tend to be designed to operate at one mode of vibration. Often these devices are tuned Langevin-type configurations with cutting tips optimised to the dynamics of the device and tailored for the intended application. However, there are several applications where the ability to rapidly switch the ultrasonic frequency in a single device would be advantageous. One example is ultrasonic surgery, where the conditions required to optimally cut soft tissues might be different to those necessary for penetrating harder tissues such as bone [1]. It is therefore of interest to define strategies to engineer adaptive ultrasonic devices suited to these applications. This study focuses on a candidate adaptive ultrasonic device based on a cymbal-type transducer, which is constructed using endcaps fabricated from the shape memory alloy Nitinol. The change in the elastic properties of the Nitinol as a function of temperature, generates an associated change in the dynamics of the device.

The cymbal transducer has been chosen as the candidate device configuration for this study. It is a type of flextensional device consisting of two cymbal-shaped endcaps attached to either side of a piezoceramic element, usually a disc. This piezoelectric element is excited by an oscillating voltage, from which the radial motions generate the desired flextensional vibration. The material properties and geometry of the endcaps dominate the transducer response, making the cymbal an ideal candidate for an adaptive ultrasonic device constructed from a shape memory material. The cymbal transducer has recently been investigated for use in surgical cutting tools [2], and in this application there are challenges associated with the efficient cutting of material which can depend on the frequency of operation. One method to address these challenges is to introduce an adaptive operating frequency capability into the device. The resonance characteristics of a cymbal transducer largely depend on the material properties and geometry of device endcaps. Recent research has shown that by integration of Nitinol into the endcaps, the resonance frequencies of the device can be successfully adjusted by controlling the temperature to which the device is exposed [3]. However, this approach has yet to be translated into a practical device concept, where increased understanding of the temperature-dependent properties of Nitinol, particularly relating to the transformation temperatures, is required for practical application.

Nitinol is a binary alloy of nickel and titanium which has found prominence in applications such as medicine and aerospace. It exhibits the shape memory effect, which is a phenomenon allowing it to recover its shape when exposed to deformation, below a certain threshold. It also displays superelasticity, which is a completely reversible response to a stress applied to the material. In the contexts of this research, Nitinol can switch between a martensitic microstructure, with a relatively low elastic modulus which can be in the order of 30-40 GPa depending on composition, and austenite, which is stiffer and whose elastic modulus can be around 70-80 GPa, again depending on composition. The transformation can occur in response to temperature, where a final austenitic transformation temperature can indicate the temperature at which the martensite to austenite transformation is complete. The impact for ultrasonic devices is that this temperature, and the elastic properties of the material, could be controlled to engineer adaptive ultrasonic devices for applications requiring multiple frequencies using a single device.

In this study, a Nitinol device is constructed using the cymbal transducer concept before characterisation is undertaken using electrical impedance analysis and laser Doppler vibrometry. The temperature of the device is then adjusted in relatively small increments towards the final austenitic transformation temperature, where comparisons with Nitinol properties are made. Practical considerations for the design and fabrication of adaptive ultrasonic devices are then explored.

II. DEVICE FABRICATION

A. Materials

A cymbal transducer is composed of two cymbal-shaped endcaps, bonded on opposite faces of a suitable piezoelectric ceramic using an appropriate bonding agent. Here, shape memory Nitinol endcaps were selected (Memry Corporation), with an external diameter of around 12.70 mm, a thickness of 0.24 mm, a base cavity diameter of 9.70 mm, and an apex cavity diameter of 4.50 mm. The cavity depth is 0.26 mm. The nominal final austenitic transformation temperature of the endcaps is 60 ± 10°C, meaning the transition from a martensitic to an austenitic microstructure should complete in this range. This transition temperature is an important design aspect, but also somewhat difficult to control based on the complexity of Nitinol endcap fabrication. Due to the challenges of machining Nitinol as desired, a piezoelectric element was selected, to be as close in diameter as possible to the endcaps. A PZ54 piezoceramic ring (Meggitt A/S) with an outer diameter of 12.00 mm, inner diameter 4.2 mm, and thickness 4 mm was selected.

B. Fabrication

The bonding agent chosen to construct the device was silver epoxy (MG Chemicals, 8331), which allows satisfactory adhesion whilst enabling electrical connection to the electrodes of the piezoelectric ceramic ring. The silver epoxy was prepared by first mixing the resin with the catalyst in a balanced 1:1 ratio. The epoxy resin was applied as shown in the exploded view of Fig. 1, before the resin was permitted to cure in a rig. The constructed device is shown in Fig. 2.

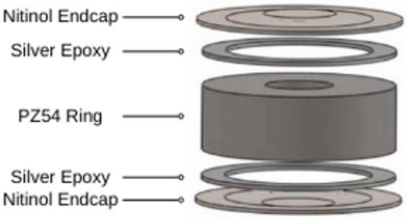

Fig. 1. Exploded view of the device and its components.

Fig. 2. The Nitinol cymbal device, where device components can be identified using Fig. 1 for reference.

III. CHARACTERISATION RESULTS

The characterisation of the Nitinol device was principally undertaken using a combination of electrical impedance analysis (EIA, Agilent 4294A, Keysight) and laser Doppler vibrometry (LDV, MSA-100-3D, Polytec). Regarding EIA, this is used to identify resonance characteristics at ambient room temperature conditions and to verify device integrity through the fabrication process, before later being used to examine the device resonance at incremental temperature steps. LDV has been used in two ways. The first is to measure the mode shape of the device, that which the device operates at its intended resonance frequency. This is undertaken using a 3D LDV system. The second is 1D LDV, where the displacement amplitude of the device can be measured as a function of excitation frequency. This is performed for different input voltage levels, thus enabling an understanding of dynamic nonlinearity.

A. Resonance Characteristics

The EIA measurements of the device, carried out at ambient room temperature, are shown in Fig. 3. It can be observed that there are two clear resonances, which can be correlated with the series resonance frequencies identified by the local impedance minima. The resonances were found to be 19.73 kHz and 23.4 kHz. The reason there are two for this device, is that in cymbal-type transducers there is commonly a mismatch between endcaps [3], for reasons including differing geometry, material properties, and bonding condition. These differences create discrepancies between the dynamics of the endcaps, and can manifest as fundamental symmetric and asymmetric cavity modes. Through EIA, it is not possible to determine which mode is the symmetric and which is the asymmetric.

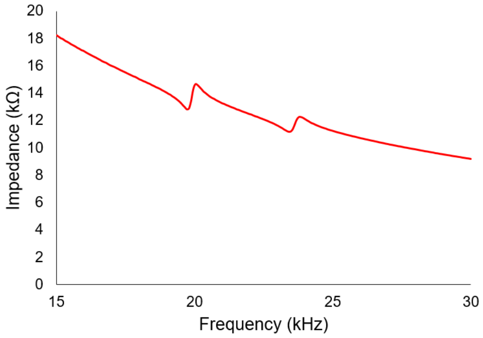

Fig. 3. EIA of the device at ambient room temperature, showing the presence of two fundamental resonant modes, one at 19.73 kHz and the other at 23.40 kHz.

In practical terms for the purposes of this study, the choice of mode on which to examine transformation performance is arbitrary. The results and discussion principally focus on the mode at 23.40 kHz.

B. Modal Response

Using the results acquired from EIA, the modal response of the device was then measured through 3D LDV. The laser spot was focused on the surface of the Nitinol endcap, perpendicular to the surface of the device. A suitable measurement window was defined to capture the entirety of the endcap surface, after which the mode shape and frequency of operation could be determined. The mode shape is shown in Fig. 4.

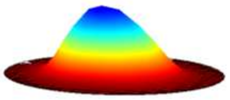

Fig. 4. Example mode shape of the device, showing resonance at 23.5 kHz. The cooler colours indicate regions of higher amplitude displacement, compared to the warmer colours.

The mode shape shown in Fig. 4 was captured at a frequency of 23.5 kHz, again at ambient room temperature. This correlates closely with the resonance frequency found using EIA. Marginal differences can be attributed to dissimilarities in the boundary condition applied to the device using each technique, and the difference in applied voltage for each method. Such minor discrepancies between EIA and LDV results are not uncommon. It was also noticeable that when analysing the endcap associated with this device mode, there was no modal response associated with the mode around 19.73 kHz that was identified in the EIA. This shows that each endcap can vibrate largely independently of one another, even in a single device.

The displacement amplitude of the device was next measured at ambient room temperature. The primary purpose of this analysis is to determine the nonlinear response of the device over a significant input voltage range. This analysis is difficult to achieve at elevated temperatures, and so an indication of device performance for different applications can be more readily acquired through 1D LDV at ambient room temperature. The laser spot from a 1D LDV system is focused at the centre of the Nitinol endcap, where the displacement amplitude is measured in incremental steps in a suitable frequency range around resonance. EIA and 3D LDV results are important to define the parameters of this experiment. The response of the device is measured when driven at input voltages from 10 V to 50 V. The results for the endcap associated with the mode at 23.40 kHz are shown in Fig. 5.

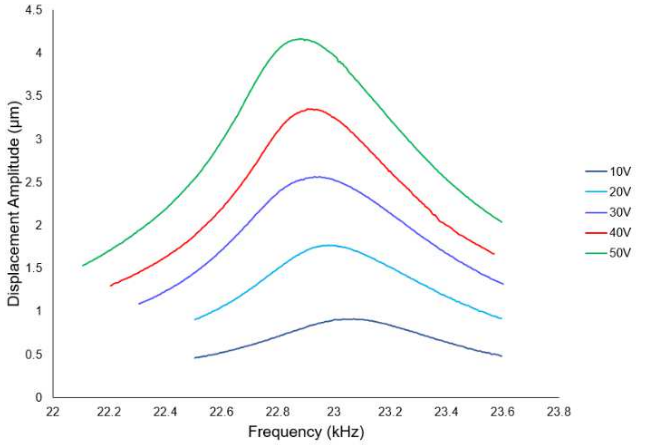

Fig. 5. Displacement amplitude responses around resonance at ambient room temperature, indicating nonlinear softening.

There is clear evidence of nonlinear softening in the dynamic response of this device. The shift in resonance, which can be identified from the peak of the curves shown in Fig. 5, shows a decrease as the input voltage is raised. This is not unusual for piezoelectric-based ultrasonic devices, but it is of interest to note competing influences from Nitinol (which can stiffen as temperature is raised), and piezoelectric (which are known to soften as input voltage, and hence temperature, is increased) materials on the device performance. Evidence from the literature shows nonlinear softening around ambient room temperature for a Nitinol device, towards hardening nonlinear as the final austenitic transformation temperature is passed [3]. The results in Fig. 5 are consistent with this, and it is evident that the nonlinearity associated with the piezoelectric material dominates the response of the device in ambient room temperature conditions.

C. *Transformation Performance*

Next, the resonance frequency of the device was monitored as its temperature was adjusted. The device was fixed into a commercial dehydrator, where the surrounding temperature was monitored using a K-type thermocouple. EIA was used to capture the resonance frequency in each case, from the electrical impedance spectra. The temperature was adjusted in 5°C increments towards 70°C, the nominal final austenitic transformation temperature of the Nitinol used to fabricate the endcaps. This was postulated to be sufficient to capture the influences of the martensitic to austenitic response in a suitably high resolution. The frequency-temperature relationship for this device is shown in Fig. 6.

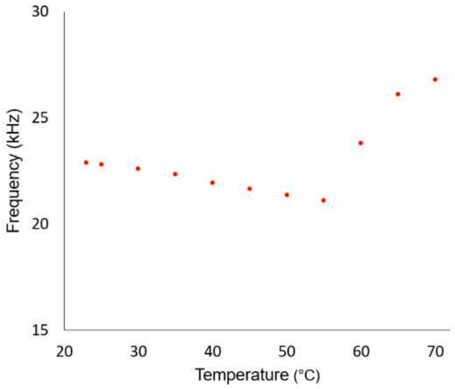

Fig. 6. Change in device operating frequency as a function of temperature, as identified through EIA.

It is notable that as the temperature is raised towards 60°C, there is a gradual reduction in resonance, after which there is a sharp increase in resonance towards that which may be expected of the Nitinol endcaps in their austenitic condition. Prior to reaching 70°C, there are likely significant competing influences from the Nitinol and the piezoelectric material on the device response, but also the epoxy resin and the integrity of the bond. The relatively thick piezoelectric element used in this device design also makes it likely that the influences from the material properties and the dynamics of this piezoceramic ring on the dynamics of the device itself are considerable. This is an important design consideration for future ultrasonic devices constructed using Nitinol.

IV. DISCUSSION

A. *Device Performance*

The results shown in Section III show that there is real scope for precise tuning of an adaptive ultrasonic device to be designed, should the material properties of the active material of interest, in this case Nitinol, be known with precision. The final austenitic transformation temperature of the Nitinol endcaps is in the 60 ± 10°C range, as per manufacturer guidance. This closely correlates with the results shown in Fig. 6, where higher resolution incremental temperature analysis has shown that once this 60°C threshold was reached, the elastic properties of the Nitinol endcaps, and hence the resonance frequency of the device, sharply increased. By introducing endcaps able to transform between martensitic and austenitic phases at a temperature of interest, it would be possible to engineer a device which could rapidly switch frequency with only modest changes to temperature. Furthermore, it is of interest to understand more regarding the physical behaviour of Nitinol, including a range of thermalmechanical responses under ultrasonic excitation. This will help to realise a new generation of adaptive ultrasonic device.

B. *Practical Considerations*

There are several key challenges identified through this research which must be overcome, to deliver practical adaptive ultrasonic devices that incorporate shape memory materials such as Nitinol. The first relates to understanding the materials used to fabricate the vibrating component of the device, in the case of this study the endcap. The influence of material processing conditions must be fully understood to define a suitable design, and the method by which the device is heated and cooled must also be tailored to the material class and the transducer configuration. The material properties, including the composition of the Nitinol itself, combined with appropriate post processing will allow a suitable transformation temperature condition to be established.

The next relates to the configuration of the transducer itself. Here, cymbal-type endcaps are used because the material volume required is comparatively low as opposed to a Langevin-type. This means the effect of temperature changes on the dynamics of the device can be more pronounced and manifest more rapidly than if a greater energy transfer was required. However, the double-peak phenomenon, where there are two fundamental operating modes in a single device, is a common occurrence in cymbal-type devices [3]. One solution for practical devices is to remove the second endcap and replace it with a suitable structure which balances the endcap dynamics. Another is to adapt the epoxy resin deposition process to remove inhomogeneities, but this is difficult. Robotic application of adhesives is well known, and this could potentially be incorporated to ensure accurate and repeatable application of the bond layer [4]. Alternatively, methods which do not require the deposition of adhesives could be explored. For example, cymbal transducers for high power ultrasonic bone surgery have successfully incorporated a bolted connection to interface between the endcaps and a back plate bonded directly to the piezoelectric disc [5]. Furthermore, there is scope to investigate how alternative configurations can be realised, considering the manufacturing challenges associated with shape memory materials.

V. CONCLUSIONS

This study has demonstrated the design and characterisation of a Nitinol ultrasonic device, with recommendations for practical application in higher power procedures such as surgical cutting. Enhanced resolution shifts in frequency response have been identified, importantly showing the feasibility of utilising Nitinol to create future adaptive ultrasonic devices which require only modest temperature changes to induce significant shifts in operating frequency. Future research will focus on fabrication methods for Nitinol-based ultrasonic devices, and a greater understanding of Nitinol response at ultrasonic frequencies.

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