Smart Cymbal Transducers with Nitinol End Caps Tunable to Multiple Operating Frequencies

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***Abstract*—Cymbal flextensional transducers have principally been adopted for sensing and actuation and their performance in higher power applications has only recently been investigated. Nitinol is a shape-memory alloy (SMA) with excellent strain recovery, durability, corrosion resistance, and fatigue strength. Although it has been incorporated in many applications, the implementation of nitinol, or any of the SMAs, in power ultrasonic applications is limited. Nitinol exhibits two phenomena, the first being the superelastic effect and the second being the shape-memory effect (SME). This paper assesses two cymbal transducers, one assembled with superelastic nitinol end caps and the other with shape-memory nitinol end caps. Characterization of the nitinol alloy before the design of such transducers is vital, so that they can be tuned to the desired operating frequencies. It is shown this can be achieved for shape-memory nitinol using differential scanning calorimetry (DSC); however, it is also shown that characterizing superelastic nitinol with DSC is problematic. Two transducers are assembled whose two operating frequencies can be tuned, and their dynamic behaviors are compared. Both transducers are shown to be tunable, with limitation for high-power applications largely being associated with the bond layer.**

I. Introduction

Cymbal transducers were developed in the 1990s [1], and have been widely adopted in low-power ultrasonic applications, such as in hydrophones and for sensing and actuation, because of their small size, capability of delivering relatively high output power, and simplicity of design and assembly. However, there are also benefits for their incorporation in high-power ultrasonic devices. Cymbals offer an opportunity to design devices where there is less need, compared with devices based on a Langevin transducer, to restrict the attached tool geometry to resonant and high-gain configurations. The development of cymbal transducers that can be tuned to more than one frequency, by integrating shape-memory alloys, is particularly applicable to many ultrasonic surgical devices, for which tailoring the performance for different hard and soft tissues can offer significant procedure enhancements.

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The cymbal transducer, a schematic of which is shown in Fig. 1, consists of a piezoceramic disc sandwiched between two metal end caps; the low-displacement radial motion of the disc causes a high-displacement axial motion of the end caps [2]. The size of a cymbal transducer is typically around 12 mm in diameter when used in ultrasound systems such as underwater hydrophone arrays [3]. The resonant frequency and axial displacement amplitudes are dependent on the geometrical dimensions of the cavity and the elastic properties of the end-cap material [4], with metals such as brass, steel, and titanium being commonly adopted [5], [6] primarily because they possess desirable elastic properties for sonar and hydrophone applications. In addition, the ease with which the end caps can be manufactured means that the geometrical dimensions of the end cap cavities can be readily tuned to generate a desired resonant frequency response. The material and geometry determine the displacement amplitude that this type of device can achieve. For example, titanium is stiffer than brass, and so will result in a device with a higher resonant frequency, but lower displacement amplitude. It has been found that, in general, cymbal transducers offer the advantage of being straightforward and inexpensive to manufacture and assemble [7] and this is especially true when end caps can be punched from a sheet metal, such as for brass, steel, and titanium.

A. Cymbal Transducer Applications

There have been many adaptations of the classical design of the cymbal transducer for different applications, although these have been largely for developments in sonar and hydrophone devices [8], which are low to medium power. The cymbal transducer is particularly suited to underwater applications because the device itself is small compared with the wavelength at resonance in water [2]. Individually, a cymbal transducer is relatively inefficient for hydrophone applications, albeit with a desirable Q-factor. Examples of improvements and design changes include a cymbal transducer with concave end caps developed to operate at high hydrostatic pressure [9], and cymbals set in array formations to enable greater radiation efficiency, output power, and directivity compared with single-element formations [8], [10]. Array configurations have also been used for transdermal drug delivery via sonophoresis [11], [12]. Cymbals have been developed as miniaturized actuators [13], as transducers for applications in energy harvesting [14], and have recently been studied for high-

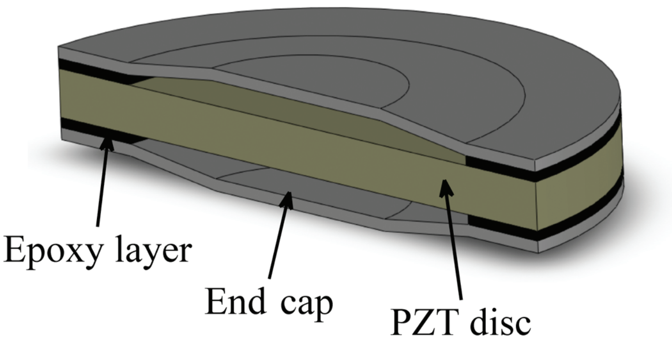

Fig. 1. Cut-away diagram of a cymbal transducer.

power ultrasonic applications [15], [16], leading to modifications of its physical coupling mechanisms to allow for excitation of the associated higher displacements [16].

Research has been conducted on the characterization of a power ultrasonic cymbal transducer configuration [15], and it is clear that in many applications there is a need for devices to operate at more than one frequency. For example, selectable-frequency ultrasonic cutting or drilling devices can allow improved penetration through layers of different materials, and cavitation activity in high-power ultrasonic vessels can be controlled by using selectable excitation frequencies to generate more tailored acoustic pressure fields. This study focuses on a modification of the design to develop a device which exhibits a tunable frequency capability. One transducer configuration that has the potential to deliver this is an adaptation of a cymbal transducer that incorporates a shape-memory alloy (SMA).

B. The Active Material Nitinol

Nickel-titanium (Ni-Ti) is a shape-memory alloy which possesses properties that were first recognized at the Naval Ordnance Laboratory (a former US Naval laboratory) in the 1960s, where it was eponymously referred to as nitinol, after its place of discovery [17]. Ni-Ti-based SMAs possess a high level of strain recovery, exhibit good corrosion resistance resulting from a passive titanium-rich oxide layer which can form on the surface of the material, can generally endure high stress levels, and are biocompatible [18], [19]. Nitinol has therefore been employed in products such as biomedical stents, orthodontic archwires, frames for spectacles, and minimally-invasive surgical devices [20]. Nitinol drills have been developed which exploit the capability of the material to deform through large angles but still perform as required. Superelastic nitinol has also been found to be attractive for the vibration control of large structures because of its high energy-dissipation capability.

Nitinol is a binary alloy which undergoes phase transitions between high-temperature austenite and low-temperature martensite, and these phases have different elastic properties and crystal structure. The elastic modulus can typically be between 20 and 40 GPa in the martensite phase and 60 to 80 GPa in the austenite phase. Forward and reverse phase transformations between cubic B2 austenite and monoclinic B19′ martensite, occur in nitinol under the application of stress or a change in temperature. However a third phase is often exhibited in nitinol alloys, especially those which are nickel-rich and have been cold-worked or subjected to certain aging heat treatments, for example, within the 350°C to 500°C temperature range. This third phase is called the R-phase, which is a rhombohedral alteration of B2 austenite [19]. It is common for the R-phase to be misinterpreted as martensite, but can usually be distinguished from martensite because there is normally a very low thermal hysteresis between austenite and the R-phase, as low as 2°C [19], much smaller than the austenite-martensite hysteresis which has poorer cyclic repeatability [19]. The phase transformations in nitinol occur via shear lattice distortion [20] and there are normally six characteristic transformation temperatures which can be identified for a particular nitinol alloy. These are the start ($_S$) and finish ($_F$) of the austenite (A), rhombohedral (R), and martensite (M) phases. The rhombohedral R-phase represents an intermediate phase which can appear when cooling from austenite to martensite; however, in several cases the R-phase can also intermediately appear in the transition from martensite to austenite [19], [21], with the corresponding transformation temperatures being designated as R'_S and R'_F [21]. A particular phase has not fully formed until the respective finish temperature has been passed. As an example, if a nitinol alloy is transforming from R-phase to austenite, there will exist a mixture of R-phase and austenite in between the A_S and A_F transformation temperatures. This will be observed until the A_F transformation temperature is reached, when the alloy microstructure has fully oriented to the austenite phase.

The properties which nitinol exhibits that are relevant and important to their adoption in tunable frequency high-power ultrasonic transducers are superelasticity and the shape-memory effect (SME). The superelastic effect is an isothermal process which occurs above the material's final austenitic transformation temperature (A_F) when it experiences a stress causing it to transform to martensite [19]. This enables a higher deformation to be recovered. The transformation temperatures are dependent on stress [17], [20], such that the material undergoes a change in microstructure, reorienting the austenite phase to the martensite phase. This effect will reverse upon unloading, because of the instability of the martensite phase at temperatures at which austenite exists. In addition, the thermal response, as with the stress–strain response, is hysteretic [22].

The shape-memory effect is stimulated via thermal loading of the material, in which a phase transition is produced by heating or cooling the nitinol to a specific characteristic transformation temperature [20]. One interesting aspect of this phenomenon is that if a nitinol component has a particular shape when it exists as martensite and is then deformed, apparently plastically, the component can be heated above its final austenitic transformation temperature, when it will recover its original (predeformation) shape, hence the term shape memory. Upon cooling, the component will retain its original shape. If the component is set to the same shape for both martensite and austenite phases, then the thermal loading will transform the microstructure from one phase to the other with no shape change.

There have been recent studies which have focused on the martensitic transformations in nitinol as a result of ultrasonic vibrations [23], [24]. It has been found that phase transformations can be induced by the application of ultrasonic energy in a nitinol alloy to produce the SME [23], and that application of ultrasonic vibrations which cause the nitinol specimen to experience cyclic stress will result in a reduced A_F. The implementation of SMAs in ultrasonic devices therefore must be based on an understanding of the effect of ultrasonic vibrations on the phase transformation behavior of the material, especially the transformation temperatures.

C. Tunable and Multiple Frequency Devices

There have been several studies reporting the development of transducers which can operate in different modes of vibration. One study has demonstrated that cymbal transducers fabricated using nitinol end caps can be used to tune the resonant frequency, and have the ability of active repair, using the shape-memory effect, for damage incurred at high hydrostatic pressures, at which the end caps can collapse [25]. Other successful developments in tunable and multiple frequency devices include a tunable vibration absorber which incorporates the magnetostrictive material Terfenol-D to control the resonant frequency of the absorber via a change of the elastic properties as a result of the magnetostrictive effect [26], a tunable ultrasonic dental scaler [27] which uses magnetostrictive scaler inserts to change the resonant frequency of the device, and a tunable ultrasonic cutting device [28] that can change resonant frequency by adjustment of the length of specific components. Nitinol has been used in tunable devices which are not ultrasonic, for example as adaptive tuned vibration absorbers (ATVAs) [29]. Nitinol has been exploited successfully in a wide range of applications, but there has been only limited research focusing on the integration of nitinol in ultrasonic transducers, especially in the development of multiple frequency or tunable devices.

The vibration behavior of two ultrasonic cymbal transducers is discussed here. The transducers are fabricated using two different end cap nitinol alloys, superelastic nitinol end caps (Johnson Matthey Noble Metals, London, UK) and shape-memory nitinol end caps (Memry GmbH, Weil am Rhein, Germany). The results show how tunable devices incorporating nitinol end caps can be successfully created and characterized to operate at two selectable frequencies. However, characterizing the transformation temperatures of superelastic and shape-memory nitinol at the device design stage, to tailor transducers to operate at specific frequencies, relies on measurements that are often misinterpreted and can be inaccurate. These measurements and their implications for design of tunable devices are also discussed.

II. Transducer Manufacture and Assembly

Commonly, cymbal transducer end caps are punched from sheet metal to ensure accuracy and repeatability in the geometry of the end cap cavities. However, there are special considerations associated with the fabrication of nitinol end caps because cold-working, chemical composition, and heat treatments can all influence the transformation temperatures. The superelastic nitinol end caps which were used in this study were manufactured to be in an oxide-free superelastic condition, with the fabrication process utilizing shape-set annealing. The binary alloy was composed of 55.99wt% Ni with a balance of Ti. Small quantities of C, O, Co, Cr, Cu, Fe, Mn, Mo, Nb, Si, and W, making up under 0.3% of the total alloy composition, were used in conjunction with precise cold-working and heat treatments to fine-tune the transformation temperatures of the material. This ensures the material is superelastic at room temperature. The shape-memory nitinol end caps were produced using cold rolling to have a final austenitic transformation temperature of 60 ± 10°C. The shape-memory binary alloy was composed of 55.11wt% Ni with a balance of Ti and small quantities of Cr, Cu, Fe, Nb, Co, C, O, and H, and was fabricated according to ASTM F2063–05 [30]. Again, precise cold-working and heat treatments were implemented to fine-tune the transformation temperatures of the material. It is difficult to manufacture end caps to the precise dimensions desired, and small variations in dimensions can have a significant influence on the resonant frequency response [4]. This is complicated by the fact that the transformation properties of the nitinol must be retained, and so the final component is produced using a careful balance between heat treatments, cold-working, and chemical composition.

Two transducers incorporating end caps of the two materials, superelastic nitinol and shape-memory nitinol, were fabricated according to the data shown in Table I. A hard PZT disc in the form of Navy Type-I Sonox P4 (CeramTec, Plochingen, Germany) constituted the piezoceramic driver material for each transducer. A layer of insulating epoxy resin (Eccobond, Ellsworth Adhesives Ltd., East Kilbride, UK) at a ratio of three parts epoxy resin to one part resin hardener was applied to the flange of each end cap before assembly of the transducer, which was left to cure at room temperature for 24 h. Fig. 2 shows a fully-assembled nitinol cymbal transducer.

The epoxy layer is nominally 40 μm thick, but is often difficult to precisely control because of the viscous nature of the deposited adhesive. In this study, an insulating, nonconductive epoxy was chosen because conductive epoxies commonly have lower bond strength [2]. Any inhomogeneities in the epoxy bond layer are usually a con-

TABLE I. Cymbal Transducer Dimensions (in Millimeters).

Transducer	Cavity apex diameter	Cavity base diameter	Cavity depth	End cap thickness	PZT thickness	Transducer diameter
Superelastic nitinol end caps	4.50	9.10	0.31	0.24	1.00	12.72
Shape-memory nitinol end caps	4.50	9.70	0.26	0.24	1.00	12.69

sequence of roughness of the end cap flange surfaces, air bubbles, and nonuniformity of deposition, which can all contribute to variations in resonant frequency [31]. Therefore, during the curing process, it was ensured that pressure was only applied to the flange of each end cap via the use of a custom rig, eliminating as many defects in the bond layer as possible and also ensuring the uniform application of pressure around each flange circumference. To ensure electrical contact between the end cap flanges and the piezoceramic disc, a small solder spot was applied to each surface of the PZT. The end caps were then bonded to the piezoceramic disc, before thin electrode wires were bonded to the flange surface of each end cap with a conductive silver epoxy (Chemtronics, Kennesaw, GA). Using a conductive epoxy to bond the electrode wires to the transducer end cap flange surfaces was preferred because of several known issues surrounding the soldering of materials to nitinol. It is known that nitinol can be difficult to solder because of the passive Ti-rich oxide layer which can form on the surface; also, any heating of the material could have undesirable effects on the material transformation temperatures [18].

III. Phase Transformation Characterization

There were four steps employed to characterize the transducers, comprising differential scanning calorimetry

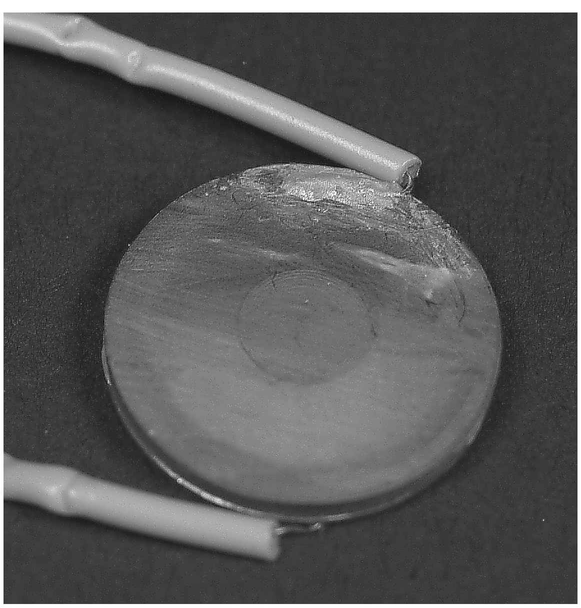

Fig. 2. A nitinol cymbal transducer.

(DSC), electrical impedance measurements (4294A, Agilent Technologies Inc., Santa Clara, CA), experimental modal analysis (EMA) using a 3-D laser Doppler vibrometer (LDV) (CLV, Polytec GmbH, Waldbronn, Germany) and vibration resonance response characterization using a 1-D LDV (Polytec CLV) to observe the displacement amplitude of each transducer at selected input voltages. DSC (Diamond DSC, Perkin Elmer, Waltham, MA; calibrated using indium) was first conducted, at scan rates of 10°C/min and 20°C/min, to obtain the transformation temperatures of the material; Fig. 3 shows the DSC analysis results for the nitinol alloys used in this study.

A sample of each nitinol alloy is exposed to a controlled thermal cycle by being heated to a predetermined temperature before being cooled again. DSC analysis allows the transformation temperatures of the material to be identified, where the endothermic reaction on heating signifies a transition to austenite, and the exothermic reaction on the cooling part of the cycle signifies a transformation to martensite. Heat flow in the sample is presented as a function of temperature. The heat flow detected in a cycle increases as the scan rate is raised because the material is being subjected to the same temperature range but over a shorter period of time. The DSC contains two furnaces, one for the sample material and the other for a reference. The power which is supplied to both furnaces is measured and monitored by the DSC, and so the increase in heat flow requires an increase in power. There are differences in the results for each alloy between the two scan rates because of this increased sensitivity to heat flow changes. The result is more discernible peaks and troughs in the response for the higher scan rate, but reduced accuracy of transformation temperature data because of the consequential thermal lag. A compromise must therefore be made in DSC analysis.

Nitinol exhibits thermal hysteresis, and this phenomenon can be observed in Fig. 3. This means that the heating and cooling cycles differ, resulting in several transformation temperatures for one particular alloy which all correspond to the start and finish of the respective material phases. Consequently, the temperature ranges for which each phase appears can be broadly identified, with the start and finish transformation temperatures extracted from the data by the intersection of the steepest slopes of the curves with the chosen baseline [19]. The transformation temperature values which are identified from the traces are therefore approximations, because there are errors associated with interpretation of these intersection points [19]. This is a limitation of the DSC technique, but in general the phase transition for each alloy is observed when the temperature is between A_S and A_F. The result-

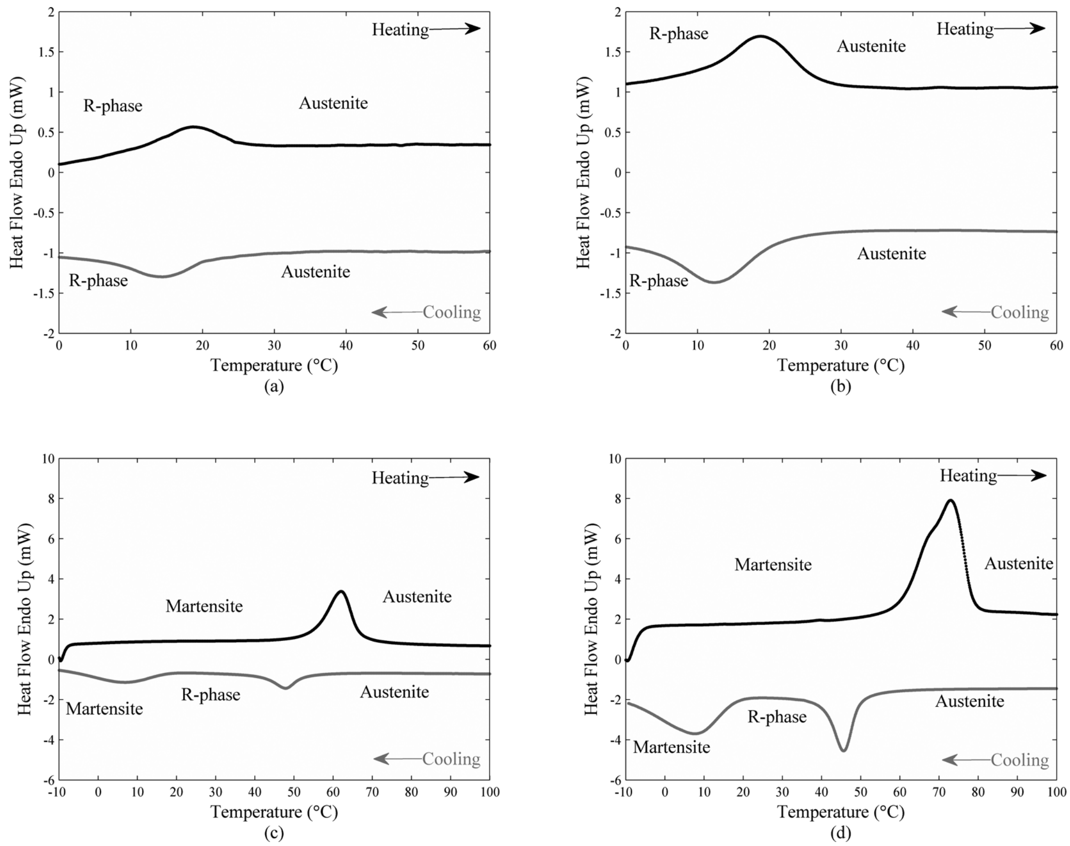

Fig. 3. DSC of superelastic nitinol end-cap material at (a) 10°C/min and (b) 20°C/min, and shape-memory nitinol end-cap material at (c) 10°C/min and (d) 20°C/min.

ing transformation temperature information from the DSC analysis is presented in Table II.

The data in Table II shows that for both alloys the transformation temperatures for a scan rate of 20°C/min are marginally higher than those identified for 10°C/min, as expected. The superelastic alloy results, shown in Figs. 3(a) and 3(b) for scan rates of 10°C/min and 20°C/min respectively, show that a very small thermal hysteresis has been detected between the austenite phase and the phase observed on the cooling cycle. This phase is the R-phase, identifiable because the thermal hysteresis between the austenite phase and that which was detected on the cooling cycle is too low for it to be a martensite phase, the thermal hysteresis being much greater for a classical austenite to martensite transition [19]. The martensite phase is not observed as it was outside the range of the test setup. The DSC results indicate that the superelastic material exhibits superelasticity from a temperature of approximately 25°C, at A_F. This means that above this temperature, sufficient stress will cause the material to reorient from austenite to stress-induced martensite, thus changing the elastic properties of the alloy. For a cymbal transducer with superelastic nitinol end caps, this should be exhibited as a change in the vibration response.

An intermediate R-phase is also observed in the cooling cycle of the shape-memory material, as can be observed from Figs. 3(c) and 3(d), and it is clear that the shape-memory material exists as austenite in the region above approximately 55°C. There is also evidence of the emergence of an intermediate R-phase in the heating cycle of the shape-memory alloy at a scan rate of 20°C/min [Fig. 3(d)], with the R-phase peak overlapped with the austenite peak, which can often occur [19]. This was not observed in the lower scan rate of 10°C/min [Fig. 3(c)], highlighting the advantage of increased sensitivity in the data. For transducer design, it is important to identify all possible phase changes in the temperature range within which the device is operating to avoid unwanted frequency changes. It is therefore advisable to characterize the material at more than one scan rate, a lower scan rate for

TABLE II. Nitinol Transformation Temperatures (°C) Extracted From DSC Analysis.

	10°C/min						20°C/min					
Scan rate	A_F	A_S	M_F	M_S	R_F	R_S	A_F	A_S	M_F	M_S	R_F	R_S
Superelastic	23	16	—	—	9	19	25	15	—	—	7	19
Shape memory	68	55	−6	16	44	52	78	61	−5	17	40	50

TABLE III. Resonant Frequencies (in Hertz) of the 2 Cymbal Transducers.

Superelastic nitinol			Shape-memory nitinol			
R-phase (22°C)	Austenite (44°C)	Change	R-phase (22°C)	Austenite (74°C)	Change	Mode
23 495	28 137	+4642 (+19.76%)	23 525	22 775	−750 (−3.19%)	Asymmetric
32 698	33 407	+709 (+2.17%)	25 650	28 800	+3150 (+12.28%)	Symmetric

transformation temperature accuracy and a higher scan rate for improved sensitivity, to have a clearer understanding of the transformation behavior.

The DSC results for the alloys show that the material can exist as either martensite or R-phase at room temperature. It is assumed that both materials exist as the R-phase for the following reasons. For the shape-memory alloy, the nitinol is fabricated at high temperatures [19], requiring cooling to produce the final condition, and the material is therefore delivered from a cooling cycle, consistent with existence in the R-phase. For this material, this was checked by conducting the DSC over a larger temperature range, cooling until the martensite phase was observed in the thermograms. If the material was supplied in the R-phase form for both alloy types, this means the microstructure should remain as R-phase when heated from room temperature until it transforms to austenite. This has significance for the design of tunable transducers. Instead of utilizing the phase change between austenite and martensite (as is usual for SMA devices) where there is a large thermal hysteresis, a smaller temperature difference can be utilized to generate a comparable frequency shift, by taking advantage of the austenite–to–R-phase transformation. This provides an opportunity to design a cymbal transducer for which two selectable resonant frequencies can be achieved through a very small change in temperature, possibly as low as 5°C.

Electrical impedance measurements were made to verify the quality of the assembled transducers, as well as to monitor the resonant frequencies and note the temperatures at which these changed. Impedance analysis is conducted at a very low excitation voltage (0.5 $V_{p\text{-}p}$) which imposes minimal stress on the nitinol, so it can be expected that only temperature effects on the impedance response are measured. The cymbal transducer under test was placed in an environmental chamber where temperature was controlled and monitored using an IR thermal camera (FLIR T425, FLIR Systems, Wilsonville, OR), to monitor the temperature of the cymbal end cap, in conjunction with a type-K thermocouple, which was used to monitor the chamber temperature. The impedance–frequency spectra of the two transducers in both the R-phase and austenite phase were measured (Fig. 4) and the resonant frequencies are recorded in Table III.

Fig. 4 and Table III demonstrate that the resonant frequencies of both transducers have been altered by a phase change. The troughs in the impedance–frequency spectra shown in Fig. 4 occur at the resonant frequencies associated with the axial modes of the transducers and the frequency shifts between the two measurement temperatures is clear. It is also noticeable for each transducer that there are two resonance responses in the impedance–frequency spectra, these being associated with two modes, the symmetric mode and asymmetric mode. The frequency of the asymmetric mode does not change as much as that of the symmetric mode between the two measurement temperatures.

The DSC results of the superelastic nitinol alloy do not correlate well with the transformation temperature required to shift the resonant frequency of the superelastic nitinol cymbal transducer. The impedance–frequency spectrum was continuously monitored as the transducer was heated to observe in real time the effect of any phase change on the response of the transducer, and it was clearly observed that the transformation to the high-temperature austenite phase occurred close to 40°C. This exhibited as a sudden increase in resonant frequency in the impedance–frequency trace during the experiment. This phase change was recorded at a temperature approximately 20°C higher than the DSC analysis suggested. For this reason, the impedance analysis was recorded at a temperature of 44°C,

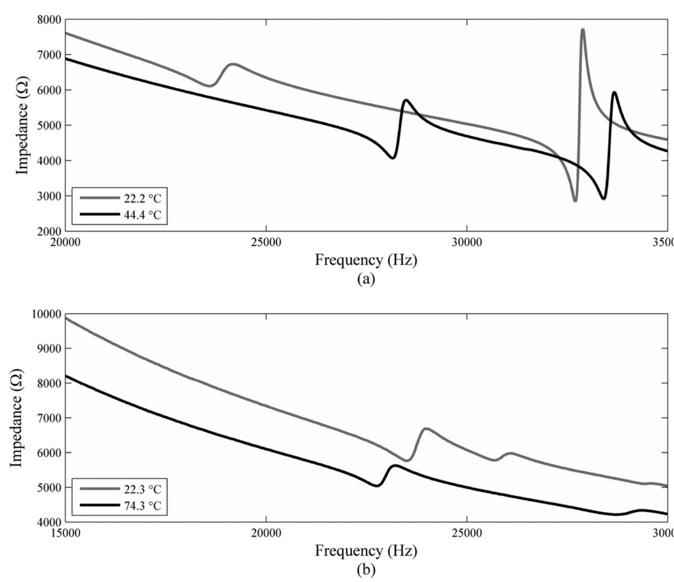

Fig. 4. Impedance-frequency spectra of the symmetric and asymmetric mode resonant frequencies for the (a) superelastic and (b) shape-memory transducer at two temperatures associated with a phase transition.

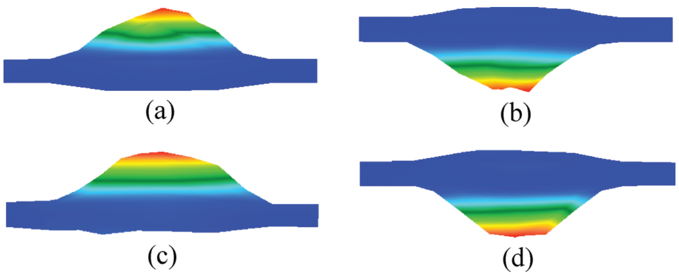

Fig. 5. Superelastic cymbal transducer (a) asymmetric (23495 Hz) and (b) symmetric (32698 Hz) modes, and shape-memory transducer (c) asymmetric (23525 Hz) and (d) symmetric (25650 Hz) modes from EMA. For (a) and (c) the lower end cap is concave, for (b) and (d) the upper end cap is convex. Blue to red indicates regions of low to high displacement.

as shown in Fig. 4(a), to ensure the measured response of the transducer was in the austenite phase. In contrast, the shape-memory nitinol transducer transformed at temperatures consistent with the DSC analysis data, resulting in the resonant frequency shift shown in Fig. 4(b).

In general, DSC is a reliable and precise technique, and the sample tests in this study were highly repeatable. It is therefore unlikely that there are any systematic DSC errors associated with the data recorded for the superelastic alloy, and this is evidenced by the fact the DSC measured transformation temperatures correlate well with the recorded phase transformation in the impedance analysis of the shape-memory transducer. It has been reported previously that DSC analysis of alloys fabricated for superelastic capability can produce inconclusive results [32], but there is no previous experimental evidence or verification reported in the literature. The data shown in Figs. 3 and 4 shows that caution must be exercised when characterizing the material behavior of superelastic nitinol which has been cold-worked, and that the consequent inconclusive interpretation of transformation temperatures has serious implications for the design of tunable transducers based on superelastic nitinol.

IV. Modal Behavior

As with most cymbal transducers, the slight asymmetries associated with transducer fabrication, including small geometrical differences between the end caps and any unevenness in the bond layer, result in the excitation of both the symmetric and the asymmetric form of the axial mode. This is commonly observed as a double-peak in the impedance–frequency spectrum [7], [33], as seen in Fig. 4. To verify the presence of these modes, experimental modal analysis (EMA) was conducted using a 3-D LDV for both transducers in the low-temperature R-phase state. The measured axial modes of each transducer are shown in Fig. 5.

The modes are confirmed as the asymmetric and symmetric axial modes. The asymmetric mode is characterized by in-phase axial motion of the two end caps, whereas the symmetric mode is characterized by out-of-phase axial motion of the end caps. However, for both modes, one of the end caps is dominant in the response. This is significant for incorporation of this transducer into a transducer, because for each resonant frequency only one of the end caps provides the axial resonant displacement amplitude that could be exploited. It is therefore important to understand the modal behavior of such devices, but also the vibration response of each mode, in particular the achievable displacement amplitudes.

V. Vibration Resonance Response Characterization

The vibration displacement response in both the low-temperature R-phase state and the high-temperature austenite phase in a frequency range around resonance in each mode was measured for both transducers, with the resonant frequencies initially as identified from the impedance analysis (Fig. 4) and EMA (Fig. 5). The two transducers were excited with a burst-sine excitation signal in bidirectional frequency sweeps through each resonance. Transducers tend to heat up as a result of extended durations of excitation during vibration characterization measurements and the consequent changes in resonant frequencies can easily be misinterpreted as nonlinear responses. The temperature of the transducers in this study also had be carefully monitored to prevent an uncontrolled phase transformation. To minimize heating in the R-phase, and to maintain consistency throughout the experiments, burst-sine signals were used with 2 to 4 s durations between bursts for all measurements, with the length of time required being dependent on the voltage level, which ensured that the cymbal transducers were maintained at room temperature. The choice of bidirectional frequency sweeps for the characterizations allowed for nonlinearities in the responses not associated with heating to be identified from any differences between the sweep-up and sweep-down responses. Experiments were conducted at five voltage levels, incremented from 2 V to 10 V. The results for the superelastic and shape-memory cymbal transducers are shown in Figs. 6 and 7, respectively.

As can be observed in Figs. 6 and 7, the measured resonant frequencies differ marginally from the resonant frequencies measured by impedance analysis and EMA. This is due, in part, to the fact that the transducers are being driven at higher voltages, meaning there are small changes in how the nitinol responds. This change in behavior has been identified in cymbal transducers fabricated using non-SMA materials such as brass [15], but it is important to clarify that nitinol is very sensitive to both temperature and strain [34], and so the higher strains excited in these experiments result in a small shift in resonant frequency greater than those resulting from much lower strain electrical impedance measurements.

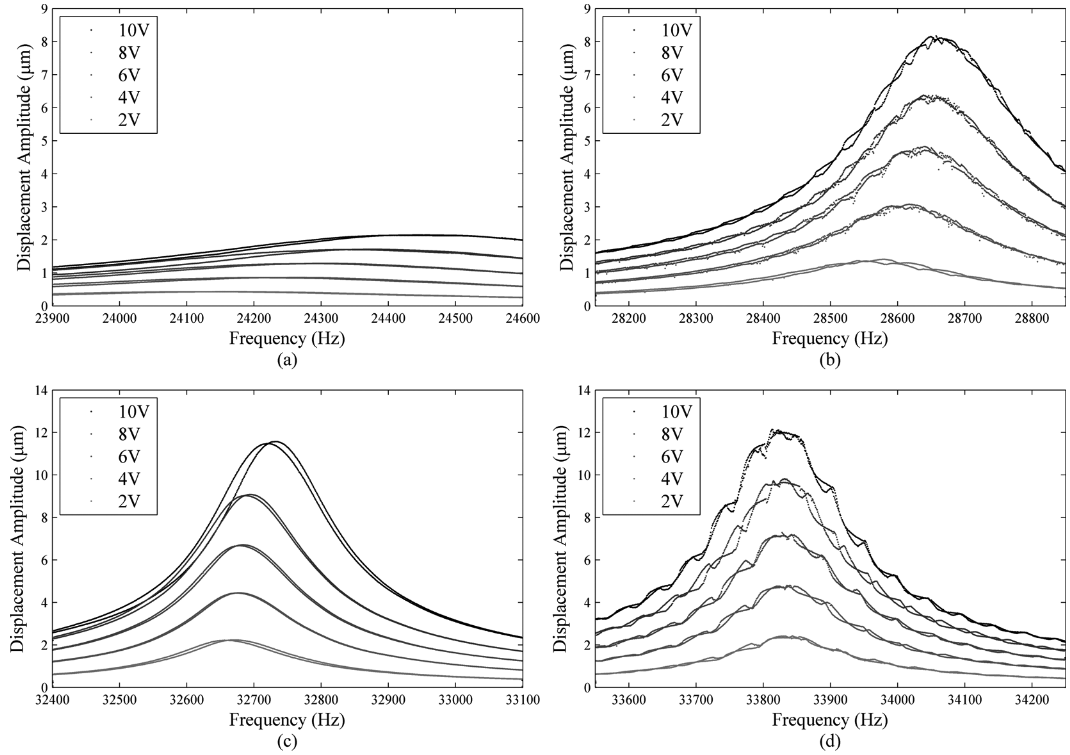

Fig. 6. Vibration responses of the asymmetric mode in the (a) R-phase (24°C) and (b) austenite phase (60°C), and symmetric mode in the (c) R-phase (24°C) and (d) austenite phase (60°C) of the superelastic transducer.

A. Limitations of the Cymbal Transducer Configuration

The results show that the phase transformation associated with each mode correlates well with the shift in resonant frequency identified in the impedance analysis. However, for both asymmetric and symmetric axial modes, lower displacement amplitude is exhibited in the R-phase compared with the austenite phase. For a pure phase transformation, one would expect the transition to a stiffer phase, for example from martensite or R-phase

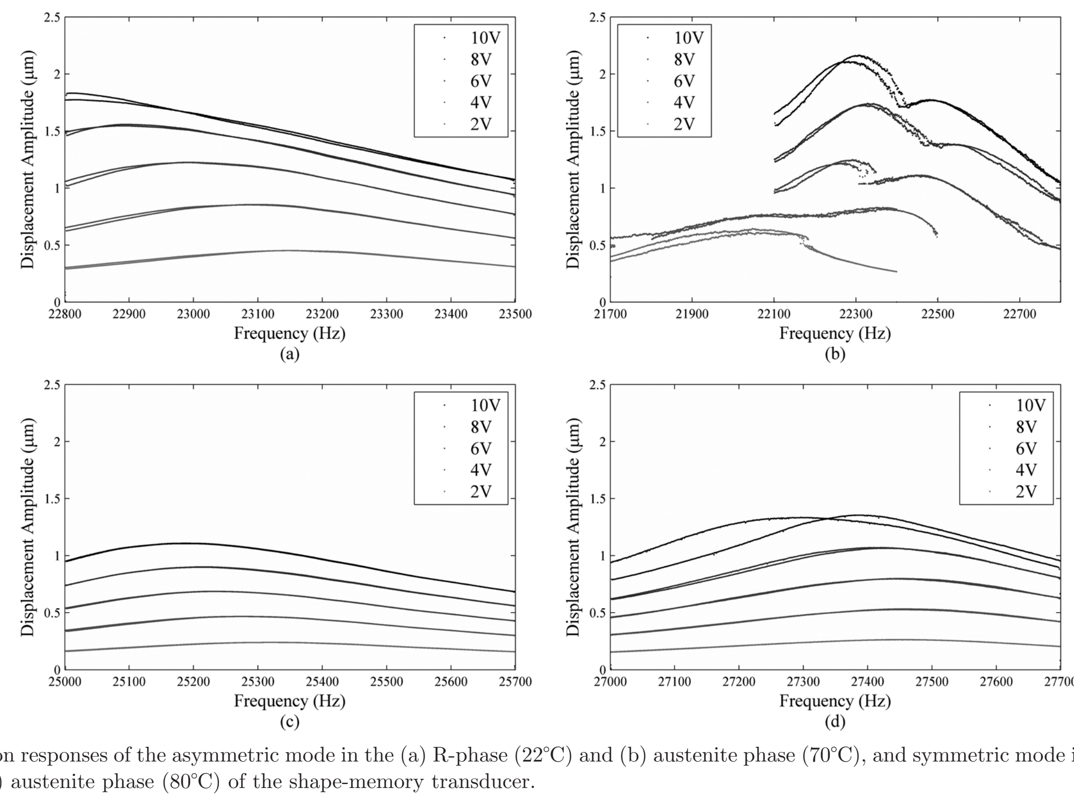

Fig. 7. Vibration responses of the asymmetric mode in the (a) R-phase (22°C) and (b) austenite phase (70°C), and symmetric mode in the (c) R-phase (24°C), and (d) austenite phase (80°C) of the shape-memory transducer.

to austenite, to result in resonance at a higher frequency accompanied by lower displacement amplitude. However, the results shown in Figs. 6 and 7 indicate that, in some circumstances, the transducers exhibit behavior inconsistent with this premise, resulting in a higher displacement amplitude and a lower resonant frequency for the shape-memory nitinol transducer asymmetric mode. Although this appears to be counterintuitive, it is important also to consider that any heating, and therefore softening, of the epoxy layer could be a major influencing factor in the measured responses. The epoxy layer is, in fact, a weakness in the classical design of cymbal transducers for higher power and higher displacement applications and different assembly configurations have been researched to overcome this limitation [15], [16].

There is further evidence that the high-temperature environment is influencing the epoxy bond layer behavior. Modulations in the frequency response are noticeable for both modes in the austenite phase in the results shown in Fig. 6. These modulations are not unique to SMA and have been similarly identified for steel-titanium cymbal transducers. It is known that raised temperatures lower the flexural and storage moduli and also the flexural strength of epoxy resin adhesives [35] and the measured responses are consistent with loss of structural integrity of the epoxy. In Fig. 7, for both modes in the higher temperature phase, the modulated distortions of the displacement response are not observed but the responses are at much lower amplitudes. This is evidence that the bond layer integrity is influenced by a combination of temperature and strain. It is worth noting that the higher temperature phase measurements are conducted close to the operational limit of the epoxy resin, which is quoted at 90°C.

B. Tunable Frequency and Nonlinear Behavior

The resonant frequency changes through a phase transformation exhibited for both the asymmetric and symmetric modes for each transducer were consistent with the electrical impedance measurements. It has been demonstrated that the superelastic transducer can be tuned via a change in temperature. However, it has not been possible to achieve a purely stress-induced martensitic transformation in the superelastic region to take advantage of the superelastic effect. This means that the stresses in the end caps of the superelastic transducer are not sufficiently high in this study. This can be investigated in further studies by exciting at much higher input voltages, but this would require a different cymbal design to avoid break-down of the epoxy layer. The shape-memory nitinol cymbal transducer was also successfully tuned, but it is evident that the asymmetric mode has experienced a split in the resonance peak in the austenite condition, as seen in Fig. 7(b), further evidence that the epoxy layer is compromised.

Nonlinear vibration responses have also been identified in the measurements of both cymbal transducers. Softening nonlinearity, in which the resonant frequency decreases as the voltage (and hence displacement amplitude) increases, is detected in the shape-memory transducer (Fig. 7), whereas the superelastic transducer exhibits global hardening (Fig. 6), in which the resonant frequency increases with voltage level. For the cymbals tested in this study, these frequency shift were very small, around 1%, but the shifts would be expected to be larger and more influential on transducer performance in high-power devices.

VI. Implications for Tunable Transducer Design

Two cymbal transducers have been designed and assembled which can change resonant frequency under a modest temperature increase. However, there are important design considerations which are apparent. There is a restriction of the DSC technique when characterizing superelastic material, and there are implications for transducer design using this type of alloy. For the design of devices to be operated in the austenite phase around room temperature, a superelastic alloy would ideally be selected because of the low A_F temperature. However, characterization of cold-worked superelastic nitinol is shown to be unreliable using DSC alone. If the transformation temperatures cannot be identified accurately at the design stage, then adoption of superelastic nitinol in tunable devices can only rely on experimental characterization of prototypes, and therefore there must be considerable leeway in the tuned frequency requirements. For applications permitting the device to be driven at higher temperatures, shape-memory nitinol is an appropriate choice.

The relationship between stress and transformation temperature of nitinol is well known [17], [20]; however, this relationship is not understood when the end caps are operating under cyclic stress conditions at high displacement amplitude. If, for example, the nitinol is heated to the austenite phase and held at a single temperature, a sufficiently high stress could cause the microstructure to reorient to R-phase or martensite. This has implications for the use of nitinol in high-power ultrasonic cymbal transducer end caps. As the stress increases, the temperature must increase to ensure a stable transformation into the higher temperature phase. Therefore, even at the high stress levels associated with high displacement amplitude, it is possible that the nitinol has not completely phase transformed and an increase in temperature is additionally required, or even higher stress.

Exploration of alternative SMAs would also be beneficial in the development of tunable cymbal transducers using active materials, which may prove to exhibit more favorable properties than nitinol. An example is $Zn_{45}Au_{30}Cu_{25}$ [36] which has been recently developed and shown to exhibit improved reversibility compared with nitinol, as well as lower thermal hysteresis and enhanced thermal cyclic repeatability.

VII. Conclusions

Tunable frequency behavior of cymbal transducers incorporating nitinol end caps has been identified and characterized using both thermal and dynamic measurement techniques. The temperature dependency of the elastic properties of nitinol can be exploited to tune the resonant frequency of a cymbal flextensional transducer. For a cymbal transducer with shape-memory end caps, it was shown that DSC of the nitinol alloy provided accurate estimations of the transformation temperatures that could be exploited to design a transducer at known tuned frequencies. However, the transformation temperatures at which a change in frequency was measured for the transducer with superelastic nitinol end caps did not correlate well with the temperatures estimated from DSC analysis. The problems identified with characterization of superelastic nitinol, particularly where it has been cold-worked, impose limitations for the design of cymbal transducers incorporating superelastic nitinol.

There is evidence of nonlinear vibration responses associated with the asymmetric and symmetric axial modes in the austenite phase and R-phase for both transducers. It is also clear that the standard cymbal transducer design is not suitable for high-power ultrasonics applications because of loss of integrity of the epoxy layer. High stress changes the phase transformation temperatures of nitinol alloys but the effects of the cyclic stresses excited in ultrasonic transducers are unknown. Nevertheless, there is potential for the design of tunable devices using active materials such as nitinol and the opportunities for tuning the operating frequency of a device through small changes in temperature are considerable.

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