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Fabrication and Characterisation of a Nitinol Langevin Transducer

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***Abstract*—A new generation of ultrasonic transducer is emerging which incorporates advanced materials such as shape memory alloys. Recently, the flextensional cymbal transducer was fabricated using the shape memory alloy Nitinol to introduce tuneable frequency dynamics for applications including adaptive sensing. The elastic properties of Nitinol are highly dependent on modest temperature shifts, hence frequency tuneability of thousands of Hz was possible. However, this has not yet been achieved for the Langevin ultrasonic transducer, one of the most common power ultrasonic classes. To investigate the opportunities for a tuneable frequency, or adaptive, Langevin transducer, this study aims to explore the fabrication challenges in transducer construction and demonstrate the dynamic characteristics of a prototype. End-masses of the Nitinol Langevin transducer were fabricated by the electrical discharge machining, after which characterisations were conducted through laser Doppler vibrometry at ambient room temperature and impedance analysis at elevated temperatures towards 50°C. Results demonstrate the tuneability of the resonance and antiresonance frequencies, in the order of 1 kHz, and their electrical impedances. This research demonstrates the potential for adaptive ultrasonic Langevin transducers for a wide range of medical and industrial applications.**

Keywords—Nitinol, Langevin transducer, electrical discharge machining, frequency tuning

I. INTRODUCTION

The Langevin transducer is a common type of ultrasonic transducer, typically composed of a front mass, back mass, a lead-zirconate titanate (PZT) stack, and a central preload bolt. Electrical energy is converted to mechanical energy at resonance based on the inverse piezoelectric effect, where the Langevin transducer can be tailored to vibrate in a specific vibration mode at a designated resonance frequency. For example, these modes can be longitudinal, torsional, or bending modes, or a combination. Through the attachment of a horn to the front mass, high vibration amplitudes can be achieved on a working tip, sufficient to deliver the required displacement amplitudes to a target. The Langevin configuration is a common choice for power ultrasonic applications, such as ultrasonic welding [1], cavitation [2], and surgery [3]. However, one key limiting feature of Langevin transducers, is that they are generally tuned to one mode of vibration and an associated resonance frequency, for a given application. The end-effectors, or working tips, which are attached to Langevin transducers are often specifically designed to integrate with the device to deliver optimal dynamic performance, including vibration amplitude at resonance. However, there has been growing interest to enable active control of device dynamics through the incorporation of advanced materials like shape memory alloys (SMAs) into ultrasonic transducers. A key example is the use of Nitinol in the flextensional cymbal transducer [4, 5]. Nitinol is a binary alloy of nickel and titanium, exhibiting both the shape memory effect, the ability to reset to a predefined shape in response to an external stimulus such as temperature, and superelasticity, which is a recovery response to sufficiently high applied stress. Its elastic modulus is significantly dependent on phase transitions between relatively low-temperature martensite to high-temperature austenite, where these transitions can occur as functions of temperature or stress. The modulus of Nitinol is known to be in the order of 30-40 GPa for martensite and 70-90 GPa for austenite [6, 7]. Prior research involving the incorporation of Nitinol into ultrasonic transducers has largely been limited to the cymbal transducer [8], where resonance frequency shifts in the order of kHz have been demonstrated [9]. These shifts in frequency are achievable, because of the magnitude of the shift in elastic modulus possible from the Nitinol component embedded in the transducer.

More recently, there has been some focus on resonance tuning of ultrasonic transducers [10, 11], though these are passive methods and there are few reports concerning the Langevin ultrasonic transducer, including for power ultrasonic applications. Such methods often do not consider materials such as SMAs, and so there is a clear opportunity to explore alternative fabrication approaches and the unique opportunities afforded by materials such as Nitinol. In this study, the SMA Nitinol is incorporated into a Langevin ultrasonic transducer to deliver a configuration with tuneable resonance characteristics. The overall aim is to demonstrate the fabrication of a prototype through a viable manufacturing process, and to exhibit the tuneability of its dynamic properties based on the temperature dependence of Nitinol's elastic moduli. Therefore, it can be shown that the Langevin transducer dynamics can be potentially tailored by temperature-induced phase transitions of an SMA.

This investigation first proposes a suitable fabrication process for the Nitinol Langevin transducer, where its Nitinol front and back masses are machined using electrical discharge machining (EDM). Then, dynamic properties of the transducer are measured at room temperature, including the mode shape and resonance frequency of the first longitudinal mode. These properties are compared to finite element analysis (FEA) results to further explore mechanical properties and for correlation purposes. To further investigate its frequency tuneability at elevated temperatures, the dynamic characteristics of the prototype are monitored from 20°C to 50°C, comprising resonance frequency, electrical impedance at resonance, antiresonance frequency, and electrical impedance at antiresonance. It is hoped that this research will progress investigations into new ways

SMAs, and other advanced materials, can be used to develop a new generation of adaptive ultrasonic technologies.

II. METHODOLOGY

A. Materials

In this study, the conventional Langevin transducer configuration has been adopted, which comprises Nitinol front and back masses, an A2-70 tool stainless steel bolt, and a PZT stack (PZ26, CTS Corporation, Illinois, USA). Nitinol material in a cylinder shape (Kellogg's Research Labs, New Hampshire, USA) with an outer diameter of 25 mm and a thickness of 10 mm was procured to fabricate the front and back masses. The final austenitic (A_F) phase transition temperature of the as-received Nitinol samples is 34.21°C, which is the temperature above which the microstructure of the material is completely austenitic, with no martensitic structures present. The hard PZT material used to construct the piezoelectric stack, PZ26, comprises an outer diameter of 20 mm, inner diameter of 10 mm, and thickness of 5 mm. Additionally, copper electrodes were manufactured by computer numerical control machining with an outer diameter of 20 mm, inner diameter of 10 mm, and thickness of 0.38 mm, to allow electrical connection across the piezoelectric stack.

B. Prototype Fabrication

The Nitinol cylinder had to be machined into suitable configurations for integration into the Langevin transducer prototype. Therefore, a central hole and a thread were introduced into the Nitinol back mass and front mass, respectively. To avoid obstructive working hardening and to mitigate defects during the manufacturing process, EDM (AD35L, Sodick Europe Ltd., Warwick, UK) was used, as shown in Fig. 1(a), with copper selected as the electrode for the EDM process, as indicated in Fig. 1(b).

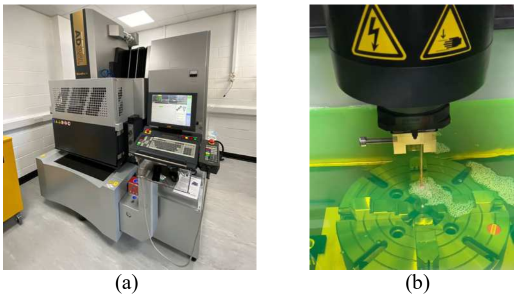
(a) (b)

Fig. 1. Fabrication of the Nitinol front and back masses, showing (a) electrical discharge machining, and (b) the manufacturing process as applied to the Nitinol cylinder.

In terms of fabrication, the work hardening of Nitinol makes it difficult to be fabricated through conventional machining methods. This is why EDM, a non-physical contact machining, was chosen. EDM involves the application of sparks to erode material from a conductive workpiece which is submerged in a dielectric liquid, and it is suitable for mitigating the risks of introducing defects to surface finish and work hardening [12]. It is also known that a thin white layer can be formed because of the resolidification of molten Nitinol by quenching, resulting in a complex phase transition and altered microstructure [13]. Therefore, there is an advantage to using EDM for fabricating Nitinol front and back masses. In this study, the oxidation layer after machining is neglected. After the EDM process was complete, the Nitinol Langevin transducer was then assembled by applying a pre-stress on the bolt, forming the required robust and stable connection between parts, as shown in Fig. 2.

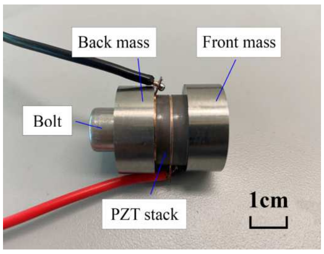

Fig. 2. The Nitinol Langevin transducer prototype.

When the pre-stress torque was set to 11 Nm, the electrical impedance of the transducer approached a minimum, thus it was defined as the optimal pre-stress value for the assembly, without risking the physical integrity of the transducer materials, such as the piezoelectric stack. However, it should be noted that the internal stresses of materials induced by the pre-stress process can affect the stability of the Langevin transducer dynamics. For example, the resonance frequency is a function of aging time. Therefore, the transducer was allowed to age for one week after fabrication, before testing.

III. RESULTS AND DISCUSSION

A. Dynamic Characterisation

The major goal of the characterisation step was to measure the vibration mode shape of the fundamental longitudinal mode and the associated resonance frequency. Only the first longitudinal mode is considered in this study since it is widely adopted in medical and industrial applications. The mode shape was measured at room temperature using laser Doppler vibrometry (LDV, MSA-100-3D, Polytec Group, Austria), and is shown in Fig. 3(a). During the measurement, the transducer was placed on the polyurethane to form boundary conditions as close to free-free as possible. An excitation voltage of 8 V was used for the LDV process to ensure sufficient vibration amplitudes such that the longitudinal vibration mode was clearly observable. The LDV system was configured to scan across the transducer structure to capture the complete modal response. To investigate the approximate elastic modulus of the Nitinol at room temperature, where the material microstructure has not reached complete austenite because it has not passed the 34.21°C A_F phase transition temperature, an FEA simulation was undertaken (Abaqus, Dassault Systèmes, France). The model and the associated resonance frequency are shown in Fig. 3(b).

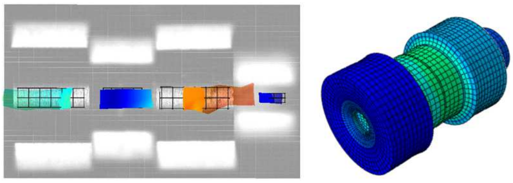
(a) (b)

Fig. 3. Mode shape of the first longitudinal mode for the Nitinol Langevin transducer at room temperature, at (a) 44.14 kHz measured using LDV, and (b) 45.67 kHz using FEA.

The principal reason that FEA is conducted at this step, is because it is known that elastic moduli of Nitinol phase microstructures are complicated to experimentally determine [14]. Therefore, at present, the design of the prototype was limited to the estimations of elastic moduli specified in Section I. However, by correlating the FEA model to the experimental results, an estimation of Nitinol elastic modulus at room temperature can be noted as in the order of GPa. This also assumes the accurate definition of the other transducer components and their material properties, but the modulus magnitude is comparable with what would be expected.

In general, the dynamic characterisation process has demonstrated a prototype resonance frequency comparable with those of configurations composed of conventional materials such as stainless steel, aluminium, and titanium front and back masses. Common medical and industrial applications utilise resonance frequencies in the low ultrasonic range, and this is consistent with the resonance frequency of the first longitudinal mode of this prototype. The successful fabrication of a Nitinol Langevin ultrasonic transducer has therefore been demonstrated.

B. Temperature Characterisation

The second part of this study focused on investigating the temperature-dependent dynamic properties of the prototype transducer, through the stated A_F phase transition temperature. There are limitations of measuring transducer dynamics at elevated temperatures, principally because the instrumentation required cannot be readily installed in those environments to obtain accurate results. Here, the mode shape and resonance frequency measured at room temperature, and shown in Fig. 3(a), were used as the reference point for monitoring shifts in transducer resonance as a function of temperature. The Nitinol transducer was positioned inside a dehydrator, where a uniformly distributed temperature field was generated around the transducer, which itself was given sufficient time to thermally equilibrate. A temperature window from 20°C to 50°C, with an interval step of 5°C, was configured, ensuring the A_F phase transition temperature was passed, thus allowing the material to transform from martensitic at room temperature, to austenitic at 50°C. It should also be noted that all measurements were conducted with the assumed free-free boundary condition at both ends of the transducer. Then, an electrical impedance analyser (Agilent 4294A, Keysight Technologies, California, USA) was used to capture the electrical impedance spectra as functions of frequency, monitored in real time as the temperature was raised. The real-time temperature was monitored using a thermocouple (RS PRO 1384, RS Components) attached to the transducer surface. The impedance-frequency spectra from 20°C to 50°C are shown in Fig. 4.

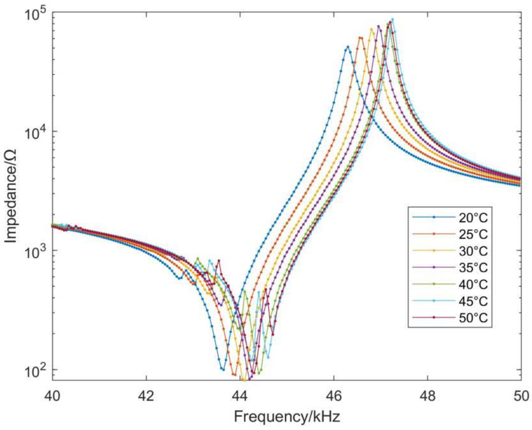

Fig. 4. Impedance spectra of the Nitinol Langevin transducer for the first longitudinal mode at elevated temperatures from 20°C to 50°C.

As shown in Fig. 4, the frequency range to encompass both resonance and antiresonance frequencies is from 40 kHz to 50 kHz. Firstly, it is evident that the resonance frequency rises with temperature, consistent with the increase in elastic modulus of Nitinol through this temperature range, and the opposite response to a transducer composed of conventional materials, those which are not SMAs. Interestingly, when the temperature rises to the approximate A_F phase transition temperature of 34.21°C, and further to 50°C, another mode in the vicinity of the first longitudinal mode becomes prominent. In order to track the expected resonance frequency of the vibration mode through the measurement process, only the major series resonances, the local minimum in each case, were considered. The dynamic properties of the prototype, comprising resonance frequency, electrical impedance at resonance, antiresonance frequency, and electrical impedance at antiresonance, were captured with respect to temperature. The results are shown in Fig. 5.

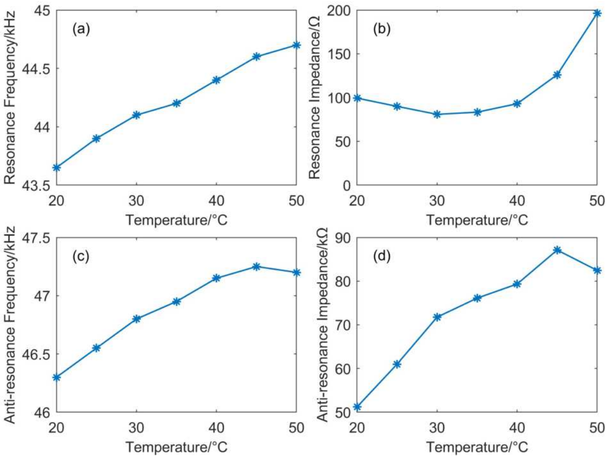

Fig. 5. Dynamic properties of the prototype in the first longitudinal mode of vibration as functions of temperature from 20°C to 50°C, showing (a) resonance frequency, (b) electrical impedance at resonance, (c) antiresonance frequency, and (d) electrical impedance at antiresonance impedance.

As shown in Fig. 5, it is evident that the dynamic properties of the Nitinol Langevin transducer are functions of temperature consistent with what would be expected given the nature of Nitinol. There is an approximately linear increase in resonance and antiresonance frequencies, both in the order of 1 kHz for a relatively modest shift in environmental temperature. This gives interesting potential applications for adaptive ultrasonic structures for industrial processes including welding.

There are also steady rises in the electrical impedances, both for the resonance and antiresonance cases, but these increases are modest in terms of resonance, being relatively stable towards the A_F phase transition temperature. It should be noted at this point, that the A_F phase transition temperature is itself an approximation from the manufacturer of the material. This property is usually determined using a thermoanalytical technique such as differential scanning calorimetry, but this was not possible for this study given the condition of the material and its size. It is also important to state that heat treatments and both hot and cold working processes can influence phase transition temperatures [15], and so there is a degree of uncertainty in the A_F phase transition temperature magnitude. Nevertheless, it is clear that the resonance frequency of the transducer has risen sufficiently to state that the austenitic of the Nitinol has been approached. Although the A_F phase transition temperature cannot be precisely correlated with the dynamic characteristics of the prototype, the changes in each property shown in Fig. 5 strongly suggest transition past the A_F phase transition temperature.

In general, the results demonstrate that the phase transition of the Nitinol front and back masses involve the rise in elastic modulus from a more compliant martensitic microstructure towards a stiffer austenitic microstructure, thus directly influencing the associated rise in prototype resonance frequency. This is entirely consistent with the dynamic responses measured on Nitinol cymbal transducers in earlier and underpinning research [4, 8, 9]. When the temperature of the environment in which the prototype is positioned passes the A_F phase transition temperature, the elastic modulus of the Nitinol microstructure increases due to this continuous phase transition, resulting the rise of prototype resonance frequency. The frequency difference at the two extremities of the temperature range demonstrates the achievable resonance tuneability of this Nitinol Langevin transducer, but with a more developed design process, this frequency gap could potentially be widened, and the required temperature range window reduced.

In this study, the EDM process has been successfully implemented in the fabrication of a prototype Nitinol Langevin transducer, where a subsequent dynamic characterisation process has been applied to demonstrate the potential dynamic tuneability of the prototype for future frequency-versatile medical and industrial applications. It has been found that, whilst complex and time consuming, EDM is a viable manufacturing method for SMA-based ultrasonic transducers, and that significant frequency tuneability in the order of 1 kHz is achievable across a relatively modest temperature range. This research opens up new opportunities for adaptive ultrasonic devices for a range of environmental conditions and tuneable resonance applications.

IV. CONCLUSION

EDM has been successfully applied in the fabrication of a prototype Nitinol Langevin ultrasonic transducer. Dynamic characterisation through LDV and electrical impedance analysis has been used to demonstrate the tuneability of the first longitudinal mode shape across hundreds of Hz, for a relatively modest range of 30°C. The phase transitions of the Nitinol used to fabricate the front and back masses of the prototype transducer have been shown to directly influence the dynamic properties of both resonance and anti-resonance modes. This study is important as it shows the fabrication and characterisation of a Langevin transducer incorporating an advanced material like Nitinol for the first time. Future research will focus on optimizing the fabrication process, the achievable frequency shifts, and the temperature window necessary, towards practical medical and industrial applications.

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