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Active Modal Coupling of a Nitinol Langevin Transducer

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Abstract—**The Langevin transducer is widely adopted for power ultrasonic applications. Its basic configuration consists of a front mass, a back mass, lead zirconate titanate rings, electrodes, and a preloading bolt. Recent research of Langevin ultrasonic actuators is focused on modal coupling, such as utilising a bending-bending coupled mode and a longitudinal-bending coupled mode to generate complex output motions. However, one challenge is that there are often notable frequency differences between the modes to be coupled, normally due to assembly and machining inconsistencies. Therefore, an active modal coupling method is proposed to overcome this, using the shape memory alloy Nitinol. The elastic modulus of Nitinol is temperature dependent, which means that the dynamics of key parts of the Langevin transducer can be actively controlled by modest variations in temperature. In this study, a Nitinol Langevin transducer is manufactured, and its temperature-dependent dynamic properties studied. Admittance, conductance, and susceptance frequencies near the resonance frequency of two out-of-plane modes were investigated over a sufficiently wide temperature range around 100°C. The results show that the phase transformation of Nitinol can be used to promote active modal coupling in a Langevin transducer comprising this material.**

Keywords—Nitinol, Langevin transducer, active modal coupling, frequency hysteresis

I. INTRODUCTION

Langevin-type ultrasonic transducers are adopted in various power ultrasonic applications, such as ultrasonic motors, scalpels, and ultrasonic drills [1-3]. The typical configuration of the Langevin transducer is a lead zirconate titanate (PZT) stack bolted to front and back masses. Typically, only one vibration mode is excited at a specific frequency. However, the application of a single vibration mode can limit the applications for which the Langevin transducer is utilised, and so modal coupling has been investigated in recent years, largely through geometrical innovations. Examples include devices exhibiting the longitudinal-bending mode [4] and bending-bending mode [5], and longitudinal-torsional mode [6].

To achieve a coupled mode, a common strategy is to design the transducer to operate at two different adjacent modes as close as possible, then operate the transducer in the intermediate frequency. Another strategy is using two same modes but with spatial and temporal phase differences at one operating frequency. Each method requires a delicate transducer design and a complex excitation approach. Therefore, a more convenient technique to facilitate modal coupling through an alternate strategy can be proposed. An active modal coupling control method is proposed in this study, based on the temperature dependent shape memory alloy (SMA) Nitinol, which can be used to fabricate the front and back masses of a Langevin transducer.

Nitinol is an approximately equiatomic binary alloy composed of the metals nickel and titanium. Nitinol has been extensively researched and has become the most widely used commercial SMA. Key properties of this alloy include the shape memory effect, superelasticity, corrosion resistance, and biocompatibility [7]. Due to these properties, Nitinol has been implemented in many applications ranging from surgical stents, brackets and wires in orthodontic applications, micro-actuators, and antennae, but apart from a few studies into flextensional transducers [8, 9], there has been limited exploration for its potential for enhancing the dynamic properties of ultrasonic devices. Nitinol exhibits three major lattice phases at varying temperatures, where the two prominent phases are martensite and austenite [10]. The martensite phase is stable at relatively low temperatures, whereas the austenite phase is stable at higher temperatures. Like other SMAs, Nitinol is desirable for its two unique properties, superelasticity and the shape memory effect, but which are as-yet under-investigated for ultrasonic applications. Superelasticity is a material phenomenon that exists when Nitinol is principally stress induced [11], and is generally an isothermal process. The shape memory effect is the ability of a material to return to its original shape after being deformed by an external load based on phase transitions in response to a thermal stimulus. The martensite phase displays a lower elastic modulus than the austenite phase because of different lattice morphologies. In the phase transition process of the shape memory effect, the temperature induces phase transformations which lead to changes in elastic properties. According to this phenomenon, a Langevin transducer can be a temperature dependent device with its dynamics being actively controlled by temperature [12].

In this study, the phase transitions of Nitinol, and hence the control of elastic modulus from around 30-40 GPa in its martensitic form to approximately 70-90 GPa in the austenitic phase, are utilised to introduce an active modal coupling mechanism for the Langevin transducer. This study investigates this coupling strategy using a combination of electrical impedance analysis and laser Doppler vibrometry (LDV). The frequency hysteresis of two adjacent out-of-plane (OP) modes is studied, where three resonance frequencies based on the electrical properties of the transducer are used as reference for the evaluation of active modal coupling. This research demonstrates the potential for advanced adaptive tuning methods for ultrasonic transducers.

II. DEVICE FABRICATION

A. *Materials*

The Langevin transducer used in this study comprises Nitinol front and back masses. Nitinol cylinders (Kellogg's Research Labs, New Hampshire, USA) were used to fabricate these masses. The martensite start (M_S) and finish temperatures (M_F) of the Nitinol cylinders were -9.77 °C and -21.01 °C respectively. The austenite start (A_S) and finish temperatures (A_F) were 23.46 °C and 34.21 °C respectively. The dimensions of the front and back masses are 25 mm in outer diameter and 10 mm in length. The material of the bolt is grade A2-70 stainless steel. The PZT stack consists of two PZ26 rings (PZ26, CTS Corporation, Illinois, USA) and two copper electrode rings.

B. *Fabrication*

The Nitinol front mass includes an M8 female thread through its length, whereas the back mass has an 8 mm hole through the component. The thread and hole are manufactured through electrical discharge machining (EDM). EDM is the most suitable way of manufacturing Nitinol as it is difficult to machine this material using traditional machining methods, largely due to the hardness and ductility of the alloy. Copper electrode rods are necessary for tapping the thread of the front mass and the hole of the back mass. The fabricated Nitinol transducer is shown in Fig. 1, which was pre-loaded using a torque of 10.5 Nm.

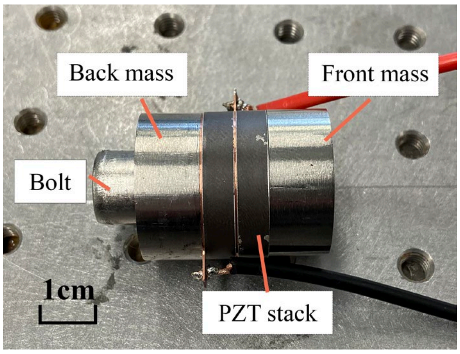

Fig. 1. The Nitinol Langevin transducer.

III. RESULTS AND DISCUSSION

This section is composed of three sub-sections. The first demonstrates the modal characterisation of the prototype transducer, where the mode shape of the transducer and the associated resonance frequency are reported. The second step exhibits the response of the transducer to temperature shifts which stimulate the phase transitions in Nitinol, and the third constitutes modal coupling analysis.

A. *Modal Characterisation*

The impedance-frequency spectrum of the Nitinol Langevin transducer was measured using an electrical impedance analyser (Agilent 4294A, Keysight Technologies, California, USA). The results from 30 kHz to 60 kHz at room temperature (around 25 °C) are shown in Fig. 2.

The impedance results demonstrate two prominent resonance frequencies of OP modes, which are designated OP1 and OP2. To visualise both mode shapes, LDV (MSA-100-3D, Polytec Group, Austria) and finite element analysis (FEA, Abaqus, Dassault Systèmes, France) were used, the results of which are shown in Fig. 3 and Fig. 4.

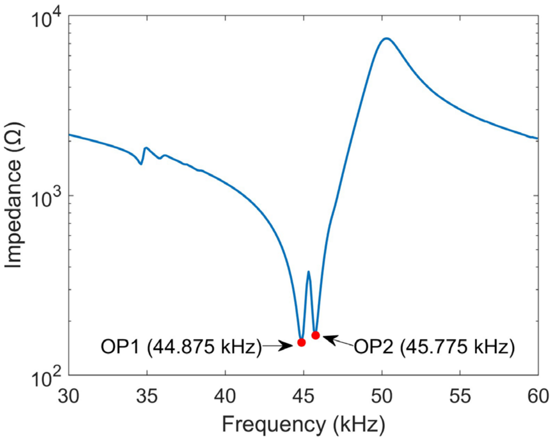

Fig. 2. Impedance spectrum of the Langevin transducer at room temperature (25 °C).

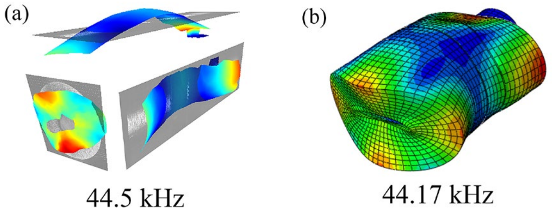

Fig. 3. Mode shapes from (a) LDV and (b) FEA results of OP1 mode.

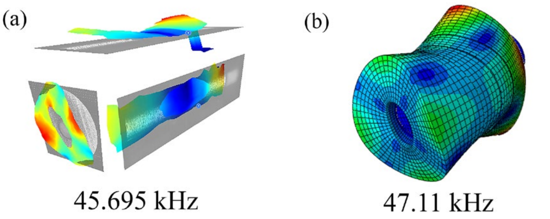

Fig. 4. Mode shapes from (a) LDV and (b) FEA results of OP2 mode.

The LDV and FEA results for OP1 and OP2 modes, from here referred to only as OP1 and OP2, correlate closely in both cases. OP1 was induced by the OP mode associated with the front and back masses, whereas the mode shape of OP2 was induced by the OP mode associated with the PZT rings. Both modes have a similar mode shape but with a 90° spatial phase difference in the circumferential direction. The modal coupling of these two modes exhibits the potential to excite a travelling wave on the end surface of the Nitinol Langevin transducer, and to realize a driving unit of a rotary ultrasonic motor.

B. *Temperature Responses*

The relationship between frequency and temperature for OP1 and OP2 was characterized by using the electrical impedance analyser connected to a commercial dehydrator for controlling the temperature to which the Langevin transducer is subjected. First, the Langevin transducer was cooled via aerosol freeze spray (RS Components) from room temperature of 25°C to -40°C, holding at -40 °C for 10 minutes and then heated by the dehydrator to 65°C. Then, the transducer was cooled from 65°C to room temperature to achieve an entire cooling-heating-cooling loop. Resonance frequencies as a function of temperature for the two modes are shown in Fig. 5.

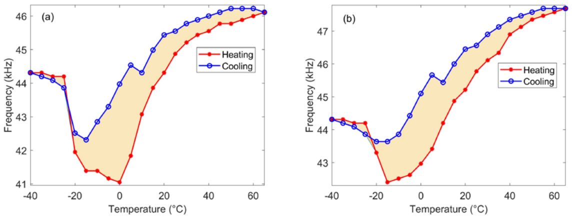

Fig. 5. Resonance frequency versus temperature for (a) OP1 and (b) OP2 in the temperature span from -40°C to 65°C.

The maximum frequency difference of each mode in the heating-cooling loop is around 5 kHz. This is over 10% of the vibration frequency at room temperature. Although temperature can affect the resonance frequency of a transducer by changing the material properties of PZT materials, for example in terms of softening, the total difference between maximum and minimum frequencies is generally lower than 10% [13]. Thus, this phenomenon demonstrates the frequency tuning capability of a Nitinol Langevin transducer. The shadowed areas between the heating and cooling processes display the achievable frequency hysteresis for a Nitinol Langevin transducer across changing temperatures. It should be noted that the hysteresis area is related to the energy which is principally absorbed by the Nitinol material subjected to an entire heating-cooling loop. This amount of energy is attributable to the transitions between the martensite and austenite phases.

Importantly, the phase transition of Nitinol leads to an elastic property change which significantly affects the resonance frequency. The trends of frequency change in both heating and cooling curves for each mode indicates the extent of the phase transition, where the higher the slope, the faster the phase transition process. These results demonstrate how the phase transitions of Nitinol embedded within the transducer contribute to a change in frequency.

OP1 exhibits particularly significant frequency shifts at temperatures from -15°C to -20°C in both heating and cooling processes. Whereas this only occurs in the heating process for OP2. This can be interpreted as the critical temperature where coupling and de-coupling occur. When the temperature approaches -25°C, OP1 and OP2 are coupled. Further research of the modal coupling effect is analysed in the next section.

C. Modal Coupling Analysis

The modal coupling is studied here principally from an electrical analysis perspective. It is necessary to consider the equivalent circuit of the transducer, which can be shown by Fig. 6 for the Nitinol Langevin transducer, as an adapted form of that reported in the literature [14].

Here, L_1 is the equivalent dynamic inductance, C_0 is the static capacitance, C_1 is the equivalent dynamic capacitance, R_1 is the equivalent dynamic resistance and U is the excitation voltage. The admittance of the equivalent circuit can be described through (1).

$$Y = i\omega C_0 + 1 / (R_1 + i\omega L_1 + (i\omega C_1) \qquad (1)$$

In (1), Y is the admittance, and ω is the radial frequency.

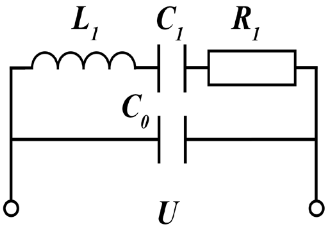

Fig. 6. Equivalent circuit of the Nitinol Langevin transducer.

The admittance is complex, where the conductance is its real part, and the susceptance is its imaginary part. Three characteristic frequencies near their resonance frequencies are the maximum admittance frequency f_a, the maximum conductance frequency f_c, and the minimum susceptance frequency f_s. The evaluation of modal coupling has been evaluated in terms of the relative frequency intervals for these three frequencies between OP1 and OP2, as shown in Fig. 7.

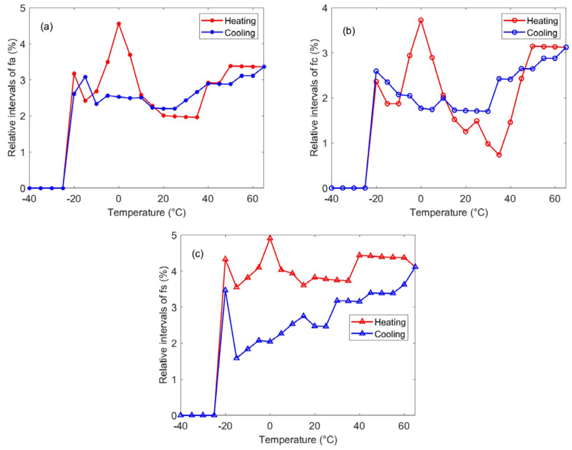

Fig. 7. Relative frequency intervals for (a) f_a, (b) f_c, and (c) f_s.

The results show the zero relative intervals for f_a below -25°C, indicating that OP1 and OP2 are coupled. In the heating process, two relative frequency interval spikes have been detected in all results at temperatures lower than 0°C and higher than 35°C. It was noticed that 0°C and 35°C are close to A_S and A_F. These two spikes, in each case, can therefore be explained in part by the changing Nitinol material properties. When the temperature is between 0°C and 35°C, the relative intervals generally decrease, especially the relative intervals for f_c. The notable decrease in Fig. 7(b) demonstrates that the phase transition of Nitinol around this temperature produces a significant effect on the conductance. It appears that the phase transition from martensite to austenite has a significant impact on the damping of the Nitinol Langevin transducer. When the temperature is higher than 50°C, all three cases of relative interval shown in Fig. 7 become generally stable. Although the temperature increases, the electrical circuit properties do not significantly change. This indicates the electro-mechanical properties are not significantly affected by the temperature, above 50°C.

In the cooling process, the relative interval magnitudes for f_a, f_c, and f_s vary gradually for temperatures higher than -20°C. The relative intervals for f_a and f_s change almost linearly, which means that the phase transition from the austenite phase to the martensite phase has a prominent effect on the admittance and susceptance. However, the relative intervals for f_c become higher when the temperature falls below -5 °C, which is close to M_S.

The results shown in Fig. 5 and Fig. 7 have demonstrated the potential for active modal coupling of a Nitinol Langevin transducer, by actively controlling the temperature to which the transducer is subjected. The hysteresis of the OP1 and OP2 resonance frequencies are related to the energy in the system arising from the phase transitions. The significant frequency differences between the heating and cooling processes can be applicable to a tuneable ultrasonic device. From a mechanical-electrical analogue viewpoint, the phase transition between the martensite and the austenite phases affects the conductance for the equivalent circuit and the damping for the mechanical system. The results demonstrate the promising potential of using temperature to realise active modal coupling for a Nitinol Langevin transducer, and there are hence new avenues of investigation open for progressing this research. This includes narrowing the temperature window and investigating the nature of the relative frequency interval changes at -20 °C.

IV. CONCLUSION

In this study, a Nitinol Langevin transducer prototype is manufactured, for which an active modal coupling method is proposed. By changing the temperature, the frequencies of two OP modes, OP1 and OP2, were tuned to show the potential of active modal coupling using the phase transition of the Nitinol material used to construct the front and back masses of the prototype. The relative frequency intervals for three frequencies near the resonance frequency have been investigated. The results show that temperature principally affects the conductance in the equivalent circuit and the damping in the mechanical system. Future research will focus on the dynamics of the coupled mode and the possibility of an active modal coupling ultrasonic device.

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