Modal Coupling Dynamics of a Nitinol Langevin Transducer

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Abstract. The Langevin transducer is a widely used device in power ultrasonics across medical and industrial fields, such as in ultrasonic motors or for ultrasonic soft and hard tissue surgeries. Although it is typically designed to operate at a particular resonant mode and one resonance frequency, there have been demonstrations of coupling specific modes together, such as longitudinal and torsional, for applications such as ultrasonically-assisted drilling. However, the challenge with this approach in practice is the inconsistency between simulation and manufacturing, in some cases limiting the coupling achievable. To solve this, the shape memory alloy Nitinol is embedded in the Langevin via end-masses, whose elastic properties can be altered with temperature or stress. Here, the aim is to show the modal coupling of two modes of a Nitinol Langevin transducer whose frequencies are dissimilar though relatively close in proximity. The results show that when the transducer temperature is below -25°C, two orthogonal vibration modes with a frequency difference in the kHz can be coupled, illustrating an active modal coupling method for practical applications.

Introduction

The Langevin transducer comprises two end-masses, a piezoelectric stack composed of interconnected piezoelectric rings and electrodes, and a central bolt used to apply preload to the structure. The aim of this study is to incorporate Nitinol, a binary shape memory alloy of nickel and titanium, into the Langevin transducer to achieve modal coupling via temperature control. The elastic modulus of Nitinol is highly dependent on its microstructure, with the modulus of lower temperature martensite ranging between 30 – 40 GPa, while that of high temperature austenite ranges between 70 – 90 GPa [1]. Such moduli shifts have the potential to tune the resonance frequencies of adjacent vibration modes in different patterns, thereby enabling modal coupling at a given temperature [2]. This may have potential uses for applications including ultrasonic motors. This study explores the coupling of adjacent out-of-plane modes of the Nitinol Langevin transducer, using the frequency response function (FRF), with frequency response analysis using heating and cooling loops.

Transducer Manufacturing and Vibration Characterisation

Shape memory Nitinol cylinders (Kellogg's Research Labs, NH, USA) were procured with an austenite finish temperature of 45°C, meaning its phase microstructure is completely austenitic above 45°C. The front and back masses of the Langevin transducer, each measuring 10 mm in length and 25 mm in diameter, were manufactured using electrical discharge machining (AD35L, Sodick Europe Ltd., UK). Then, the Nitinol Langevin transducer was assembled by aligning a stack of lead zirconate titanate (PZT) rings between end-masses using a preload torque of 10.5 Nm through an M8 stainless steel central bolt, as shown in Fig. 1(a). Two adjacent out-of-plane (OP) mode shapes were observed using a 3-D scanning laser Doppler vibrometer (LDV, MSA-100-3D, Polytec GmbH, Germany), as illustrated in Fig. 1(b). Using an 8 V excitation, OP 1 and OP 2 were measured at 44.5 kHz and 45.965 kHz, respectively.

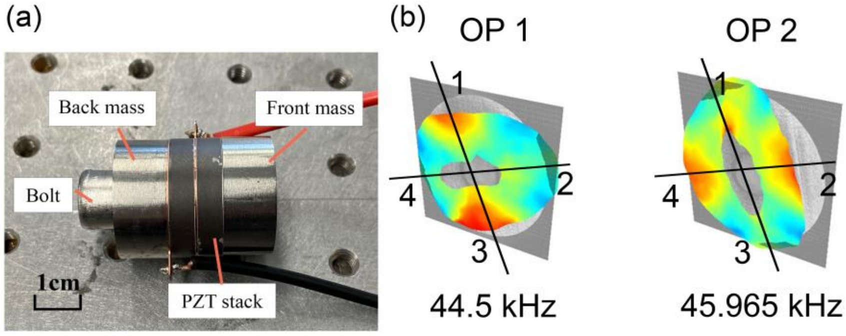

Fig. 1: (a) The prototype Nitinol Langevin transducer, and (b) mode shapes at 44.5 kHz and 45.965 kHz [2].

A 3-D LDV (CLV3000, Polytec GmbH, Germany) was utilised to obtain the FRFs in a spatial coordinate system, which exhibits the dynamic response of four set points on the end section surface, as shown in Fig. 2. Specifically, the FRF magnitude and the corresponding vibration amplitude are higher for the OP1 mode at points 1 and 3, while for the OP2 mode, they are higher at points 2 and 4.

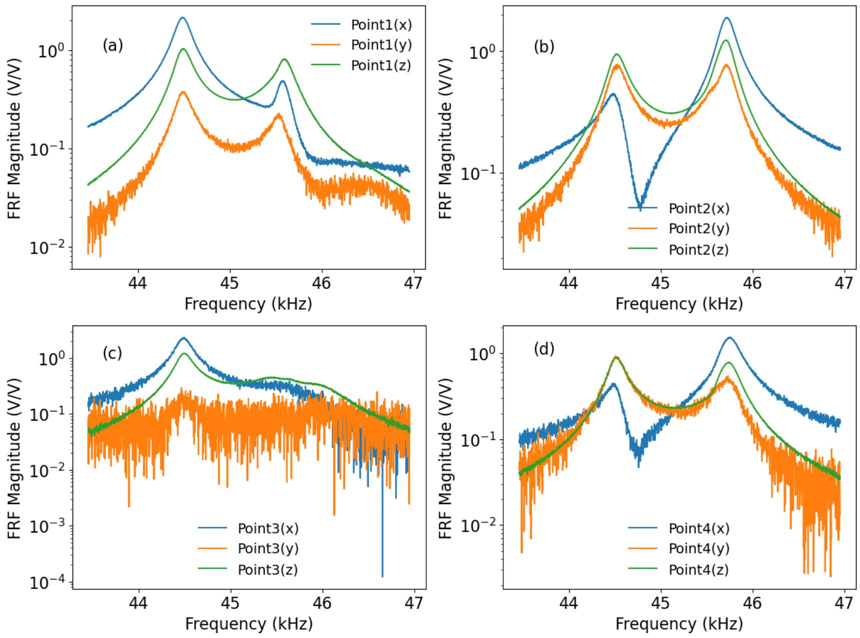

Fig. 2: FRFs for (a) point 1, (b) point 2, (c) point 3, and (d) point 4 on the end section surface.

Frequency Responses at Different Temperatures

An electrical impedance analyser (Agilent 4294A, Keysight Technologies, CA, USA) was used to monitor the frequency response of the two OP modes, where the transducer temperature was maintained within a window of -40°C to +60°C. To achieve this, a commercial dehydrator (Andrew James, UK) and aerosol spray were used for heating and cooling the transducer, respectively. Both thermal hysteresis and modal coupling were then investigated for the Nitinol Langevin transducer, through a heating and cooling cycle, as shown in Fig. 3.

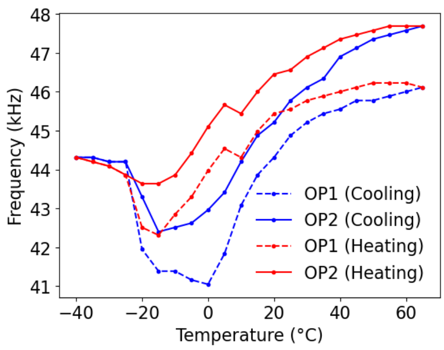

Fig. 3: Frequency responses for OP1 and OP2 modes across the temperature window from -40°C to +60°C.

The results demonstrate that for temperatures below -25°C, adjacent OP modes are coupled, even with a 1 kHz difference at room temperature. This is likely because Nitinol's Young's modulus is highly temperature dependent, resulting in distinct frequency shifting patterns of two OP modes with regards to temperature. Future work will focus on modal coupling at ambient room temperatures, to widen application potential.

Conclusion

A Nitinol Langevin transducer has been manufactured and characterised to achieve modal coupling. The vibration mode shapes and FRFs at room temperature for two adjacent OP modes have shown that they are orthogonal and exhibit varying levels of vibration amplitude on four end surface points. The resonance frequencies of the two modes are coupled when the transducer temperature is below -25°C. This presents an opportunity to establish a travelling wave on the end surface via orthogonal modal coupling. Further work will focus on demonstrating active modal coupling at higher temperatures for room temperature applications.

References

[1] Y. Liu, M. Hafezi and A. Feeney: *Fabrication and Characterisation of a Nitinol Langevin Transducer*, IEEE International Ultrasonics Symposium (IUS) 2023 Sep 3, p. 1-4.

[2] Y. Liu, M. Hafezi and A. Feeney: *Active Modal Coupling of a Nitinol Langevin Transducer*, IEEE International Ultrasonics Symposium (IUS) 2023 Sep 3, p. 1-4.