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Characterization and post simulation of thin-film PZT actuated plates for haptic applications

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Abstract

The tremendous development of tactile interface in many customers' applications such as Smartphone, tablet PC or touch pad leads industrials to study "haptic interfaces" or "touch screen" solutions. This technology is already used but with limitations such as high power consumption and limited feedback effect (simple vibration). PZT is a good candidate for many actuator applications due to its high piezoelectric coefficient. In particular, it can be used for haptic interfaces to create squeeze-film effect. It consists in changing the friction between the finger and a plate resonator. It provides high granularity level of haptic sensation (texture rendering), using low power consumption compared to existing solutions. We manufactured demonstrators using a generic technology. We proved the concept through electro-mechanical characterizations and haptic feedback effect was noticeable with one's finger on our thin-film PZT demonstrators. In this paper, we presented the characterization and post-simulation of PZT-actuated plates with various actuator configurations. Measurement results, in good agreement with simulation, indicate that 2 actuator columns separated by a wavelength allow obtaining the highest substrate displacement amplitudes.

1. Introduction

Many applications can be concerned by high performances, low voltage haptic interfaces which allow the user to interact with its environment by the sense of touch. We developed sol-gel thin-film $\text{Pb}(\text{Zr}_{0.52}, \text{Ti}_{0.48})\text{O}_3$ (PZT) actuated plates allowing the feeling of textured surfaces. It consists in changing the friction between the finger and a plate resonator due to the squeeze-film effect, which occurs when the plate displacement amplitude reaches about $1\mu\text{m}$ in a flexural anti symmetric Lamb mode [1, 2]. It provides high granularity level of haptic sensation (texture rendering), using low power consumption compared to existing solutions.

We manufactured demonstrators using a generic technology compatible with RF MEMS [3], loudspeakers [4] or micro mirror [5]. We proved the concept through electro-mechanical characterizations. Laser vibrometer measurements indicate that our PZT actuator design promotes the desired mode with the

targeted amplitude. Haptic feedback effect was noticeable with one's finger on our thin-film PZT demonstrators [6].

This paper reports on the design, the characterization and the post-simulation of thin-film PZT actuated haptic plates. We developed predictive model, and in particular we studied the best actuator configuration in order to promote the highest substrate displacement amplitude.

2. Design

We designed high performances thin-film PZT actuated haptic plates using Finite Element Method (FEM) approach (*CoventorWareTM*). All simulations are performed using an unclamped $725\mu\text{m}$ thick Silicon substrate as resonant plate. Our model neglects top and bottom electrodes which sandwiched the $2\mu\text{m}$ thick PZT layer due to their weak impact on simulation results. We used *Manhattan* bricks to mesh the haptic plate. As input data, we used the thin-film PZT d_{31} piezoelectric coefficient, namely 165 pm/V [7], the PZT Young's modulus $E_{\text{PZT}} = 82\text{ GPa}$ and Poisson's ratio $\nu = 0.39$ [8].

We already proved that the maximum substrate displacement amplitude of our haptic plate can be obtained by taking the deformed shape of the selected mode into account, and matching the actuators position with the substrate maximum displacement amplitude as shown in Figure 1. PZT actuators promote the desired mode by bimorph effect [6].

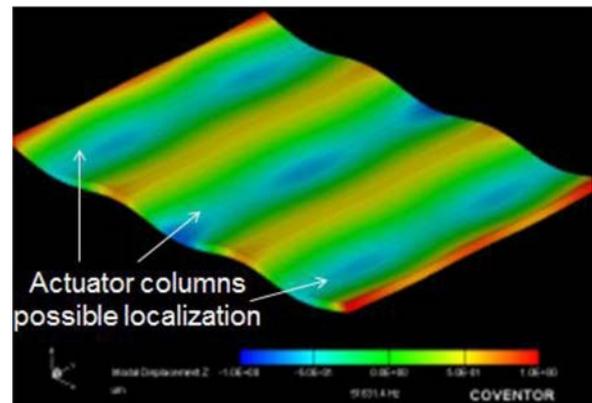


Figure 1: Modal simulation (51.89 kHz) on a $40\times 30\text{ mm}^2$ plate and PZT actuator columns possible localization.

As shown in Figure 1, various PZT actuator configurations are possible. In particular, we studied:

- 1 actuator column,
- 2 actuator columns separated by a wavelength: in this case the actuator columns are located on successive in-phase maximal substrate displacement amplitude areas,
- 2 actuator columns located at the extremities of the plate: the actuator columns are located on in-phase maximal substrate displacement areas near the ends of the plate.

For each studied configuration, we first performed a modal simulation in order to define the frequency of the desired mode. Then relative harmonic simulations were performed using arbitrary damping parameters and a given actuation voltage. As shown in Figure 2, two actuators columns separated by a wavelength induce the highest substrate displacement amplitude for both 60×40 and 40×30 mm² plates.

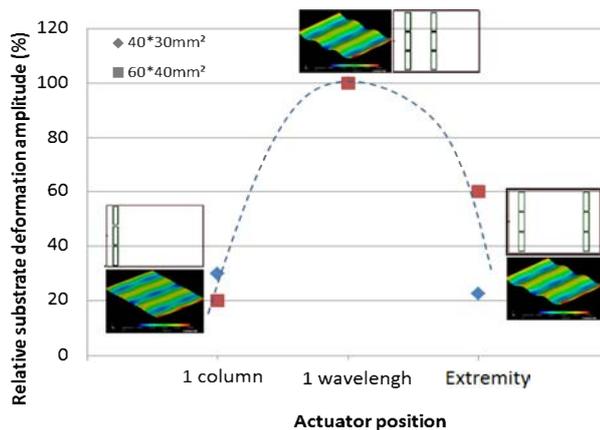


Figure 2: Harmonic simulations with arbitrary damping parameter study – Actuator columns configuration study for both, 60×40 and 40×30 mm² plate.

3. Technology

Devices were manufactured out of 200 mm standard silicon wafers. First step is a 500 nm thick thermal oxidation (SiO₂). Then, the piezoelectric stack, which consists of 2 μm thick sol-gel PZT in between 100 nm thick Pt bottom electrode and 100 nm thick Ru top electrode, was deposited and etched. We deposited and patterned a passivation silicon oxide layer followed by gold lines and pads. Figure 3 gives a cross section view of the technological stack as well as a SEM cross section of the PZT actuator. Only 5 photolithography masks were necessary to build the demonstrators.

Finally, we sawed the substrate to transfer the individual plate onto a mechanical support allowing to hold the vibrating plate and to connect it electrically. The plate was fixed by an adhesive tape and the actuators were wire bonded to electrical connectors. Figure 4 gives an example of a 60×40 mm² plate ready for electrical characterization.

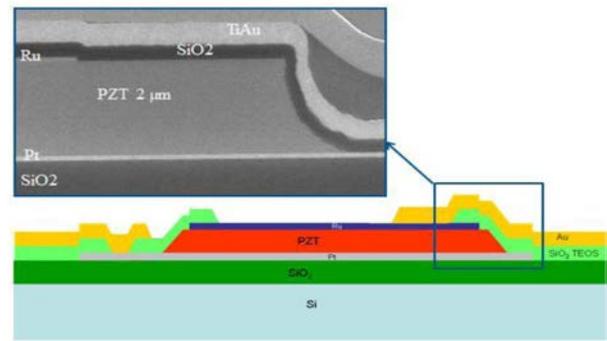


Figure 3: Schematic cross section of the technological stack and SEM cross section of the PZT actuator.

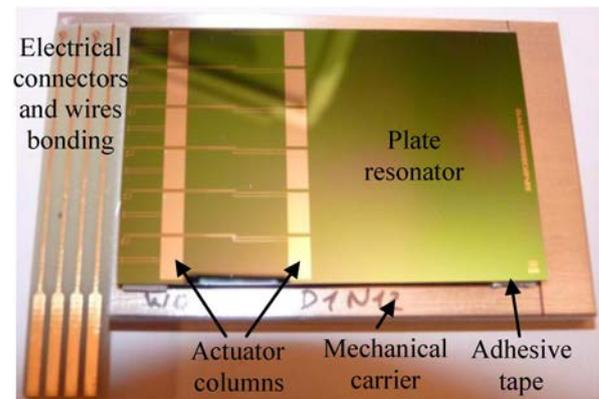


Figure 4: 60×40 mm² plate fixed on a carrier using adhesive tape and with PZT actuators bonded to electrical connectors.

4. Electromechanical characterization and post-simulation

Optical measurements were performed using a laser vibrometer (POLYTEC) by applying a dc-ac mixed voltage to the top electrode of plates (60×40 or 40×30 mm²). Laser vibrometer measurements give the substrate displacement amplitude for a given actuation voltage. Several measurements have been necessary to build the plate's whole picture given in Figure 5. This picture allows us to validate that the studied mode is the flexural antisymmetric Lamb mode required for haptic applications. We measured the desired resonant mode at 32.2 kHz for the 60×40 mm² plate. The agreement between measurements and simulations is satisfactory. Indeed a discrepancy lower than 1% is noticed. Moreover, we note that the substrate displacement amplitude reached 500 nm under 4V ac/peak to peak. This value is very satisfactory for such a low actuation voltage.

Using FEM approach, we adjusted a damping parameter to fit the substrate displacement amplitude previously measured. Figure 6 gives the comparison between the simulated substrate displacement amplitude and the measured one under 4V. It allows us to determine that a damping parameter of 2.5·10⁻⁸ is necessary to fit measurement for 60×40 mm² plates.

Only one damping parameter per plate sizes was used as reported in Table 1.

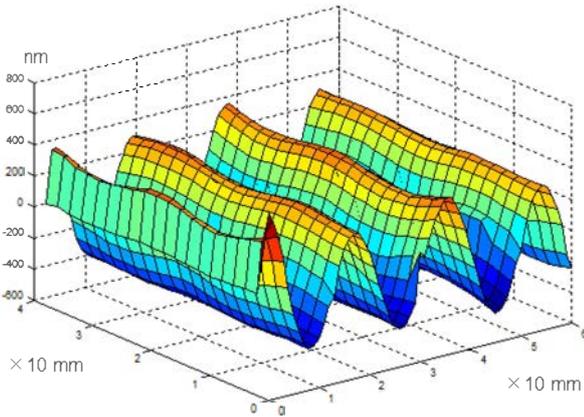


Figure 5: Laser vibrometer measurement on the 60×40 mm² plate (12V_{dc}+4V_{ac/pp}). Resonant frequency measured at 32.2 kHz.

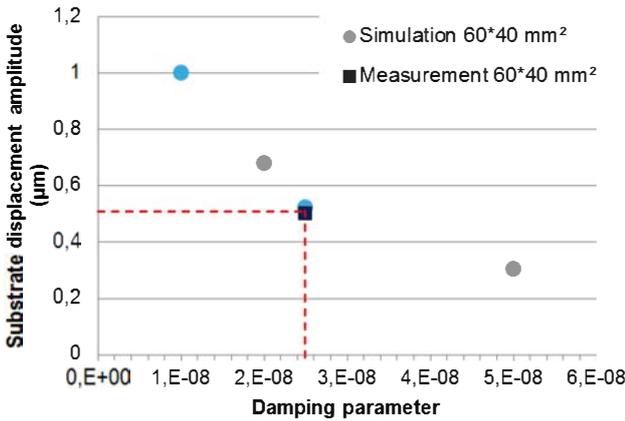


Figure 6: Comparison between the simulated and the measured substrate displacement amplitude of a 60×40 mm² plate under 4V for damping parameter identification.

Plate size (mm ²)	Damping parameter
60×40	2.5.10 ⁻⁸
40×30	10 ⁻⁸

Table 1: Damping parameter function of the plate size.

For example, with a damping parameter of 2.5.10⁻⁸, we can post-simulate a 60×40 mm² plate as shown in Figure 7 (discrepancy < 5%). One can note the micrometric displacement amplitude, namely 1.1μm, obtained using only 8V ac/peak to peak. A haptic feedback effect was felt with the finger on this plate by using an actuation signal modulated at 10 Hz in amplitude [6].

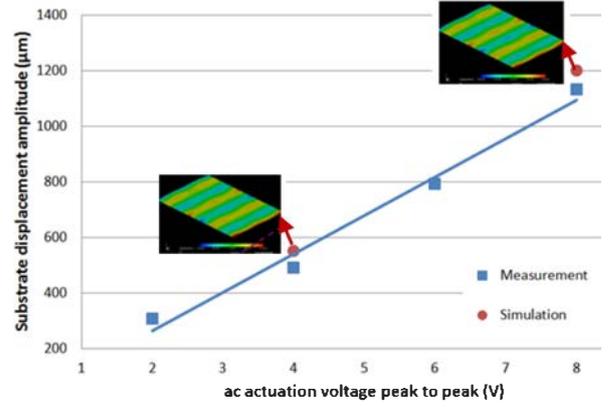


Figure 7: Laser vibrometer measurements and simulated substrate vertical displacement (pictures) amplitude comparison on a 60×40 mm² plate (12V_{dc}+variable V_{ac/pp}).

Both on 60×40 and 40×30 mm² plates, the best actuator columns configuration were studied. As shown in Figure 8, measurements results obtained using 12V_{dc} + 4V_{ac/pp}, in good agreement with simulation, indicates that 2 actuator columns separated from each other by a wavelength allow obtaining the highest substrate displacement amplitude. Unfortunately, most of the targeted applications require transparency, at least of the center of the plate, and this actuator configuration induces a large opaque zone (dead area). Consequently it will only be retained if transparency is not required by the focused application.

We note on Figure 8 that the measured substrate displacement amplitude with 2 actuator columns located at the plate ends is only 5% smaller for 40×30 mm² plates and 11% smaller for 60×40 mm² plates, compared to the best configuration discussed previously. This configuration presents a larger area dedicated to touch experience. It will be favored, for example for Smartphone applications, for which we have to preserve the largest transparent surface as possible, dedicated for touch experience.

Finally the last configuration with only one actuator column presents the smaller dead area. It induces measured substrate displacement amplitude respectively 46 and 88% smaller for 40×30 and 60×40 mm² plates, compared to the best configuration discussed previously. In the case of the characterized 40×30 mm² plate, the measured substrate displacement amplitude is all the same satisfactory for such a low actuation voltage. FEM simulation indicates that we can reach the micrometric substrate displacement amplitude required for haptic application under 14 V_{ac}. In the case of the characterized 60×40 mm² plate, the low measured substrate displacement amplitude can result from a malfunction of the device. Further measurements must be performed to confirm this experimental result. This configuration can be retained for applications that need the smallest non-transparent dead area, to the detriment of low actuation voltage.

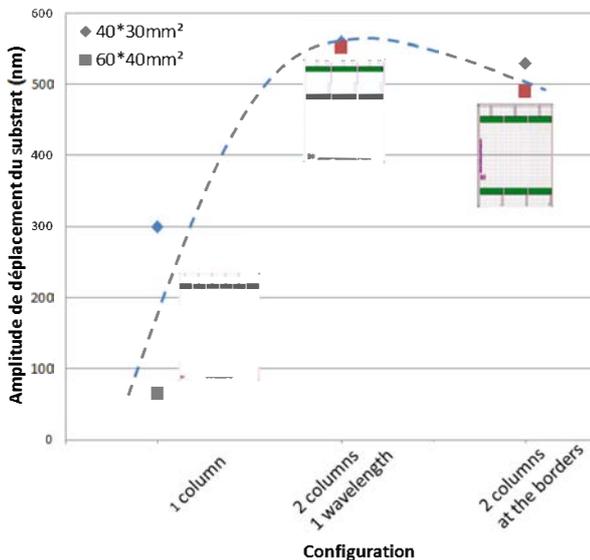


Figure 8: Laser vibrometer measurements -Substrate vertical displacement amplitudes on 60×40 and 40×30 mm² plate presenting various actuator configurations (12V_{ac}+4V_{ac/pp}).

5. Conclusion

We have developed a unique solution based on PZT thin-film actuated plates allowing haptic feedback effect using low bias voltage due to squeeze-film effect. In this paper, we presented the characterization and post-simulation of PZT-actuated plates with various actuator configurations. Measurement results, in good agreement with simulations, indicate that 2 actuator columns separated by a wavelength allow the highest substrate displacement amplitudes. But this configuration, inducing a large non-transparent zone, occupied by actuators, will be retained if transparency is not required by the focused application. The second configuration, with 2 actuator columns located at the plate ends presents substrate displacement amplitude slightly smaller compared to the best configuration, but exhibits a larger area dedicated to touch experience. This configuration will be favored for example for Smartphone applications for which we have to preserve the largest transparent surface as possible. Finally, the configuration with only one actuator column presents the smaller dead area. It induces smaller substrate displacement amplitude compared to the best configuration. This configuration will be favored for the applications requiring the smallest non-transparent dead area, to the detriment of low actuation voltage.

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