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Research Article

Development of a Thin Vibrotactile Actuator Based on the Electrostatic Force Mechanism for Large Haptic Touch Interfaces

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Vibrotactile feedback in touch screen displays (TSDs) contributes to improved usability and enhanced engagement. It is prevalent in small consumer electronic devices, such as smart phones. While vibrotactile feedback is a desirable feature for large TSDs, it is limited in such devices due to a lack of proper actuators. In this study, we propose a thin vibrotactile actuator based on an electrostatic force mechanism suitable for mounting on the back of large TSDs. The primary goals of this study are to design and test a thin or slim electrostatic resonant actuator (ERA) and investigate its feasibility for large TSD applications. A prototype ERA was constructed by employing a "leaf" spring design to reduce the thickness and to support a mass that is grounded electrically. Upon applying a high-voltage input to the prototype, the electrostatic attraction force coupled with the spring's restoring force makes the mass to oscillate, and the maximum vibration occurs at its resonant frequency. The ERA module testing shows that the prototype produced the maximum output acceleration of 2.5 g at its resonance frequency (99 Hz), which is significantly larger than the threshold value which humans can perceive. After validating that the thin ERA can produce sufficient vibrotactile sensations, a haptic touch display module consisting of a 17-inch touch panel supported by four ERAs was constructed. To experimentally evaluate the performance of this prototype, three distant input frequencies were used, and the acceleration response of the panel was measured at multiple points. The results show that the acceleration magnitude varies, exhibiting distinct patterns throughout the panel surface, when different input frequency values were applied. The results further show that the maximum acceleration magnitude is greater than that of the human-perceivable threshold values for the input frequencies considered in this study. Overall, the results show that the proposed ERA is feasible to use in large TSDs to convey vibration tactile sensations to users while keeping the thickness of the haptic interface module thin.

1. Introduction

The touch screen display (TSD) used in mobile devices, such as smartphones and tablets, allows the user to interact with the device more intuitively with improved features as compared with the input with old-fashioned physical buttons [1]. In particular, the advancement of the tactile feedback technology in TSDs has significantly improved the input speed, accuracy, and realistic physical interactions such as physical button clicks [2–5]. Recently, the application of TSDs has expanded in various fields that include education, training, and vehicles [6, 7]. Particularly, large-sized TSDs are broadly applied in kiosks, digital advertisement banners, and control displays in medical devices and automobiles [8]. Needless to say, there is a great demand in the industry for the application of the vibration tactile feedback features that are available in mobile devices to large TSDs. As an example, "smart" cars in the automotive

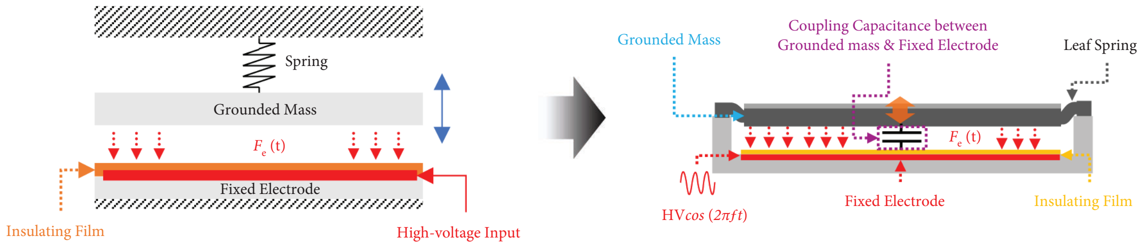


Figure 1: Illustration of working principles: (a) Electrostatic parallel plate actuator and (b) Proposed thin electrostatic resonant actuator.

industry replace the center console equipped with mechanical buttons and knobs with TSDs, and vibrotactile feedback features in TSDs greatly improve driver safety [5]. In order to meet the demand for large TSDs, it is imperative to develop actuators capable of generating vibrotactile sensations that are sufficiently large magnitudes. Various types of vibrotactile actuators, such as linear resonant actuators (LRA) and piezo actuators (PA), have proven to be highly effective in producing vibrotactile sensations, and some have been successfully used in commercial mobile devices (for example, Taptic Engines) [9–12]. However, being designed primarily for mobile devices, these actuators are small and lightweight, so they are not suitable for large TSDs where substantially larger vibrotactile feedback is needed. Consequently, it is required to develop an actuator capable of generating vibrotactile feedback of sufficient magnitude in large TSDs.

Another method of generating tactile feedback in TSDs is to use static electricity to generate an attractive force between the user's finger and electrodes to directly transmit electrical vibrations to the skin. This is a method to control vibrotactile feedback by controlling the force of an electrically charged surface pulling the skin of the user's finger [13]. This technology was developed to replace the mechanical vibrotactile method in TSD, but it transmits the tactile sense only when the finger slides on the surface, making it impossible to create a button sensation, and the generated tactile feedback depends on humidity and temperature [14–17]. Although the electrostatic force mechanism has the advantage of simply generating attractive forces in a separate thin plate-like structure, it has been mainly applied only to micromachined devices due to its small output performance [18]. However, the electrostatic force has the advantage that the output force increases linearly as the electrode area increases [19], so there is a possibility that a fairly large output force can be generated when it is thinly and widely mounted on the rear surface of a large TSD. Additionally, if one electrode is made of a spring structure and driven at a resonant frequency, the vibration output can be greatly amplified. Exploiting the working principle of electrostatic parallel plate vibration actuators, Koo et al. developed a vibration actuator that drives a spring-mounted mass up and down with electrostatic force [20]. They demonstrated that electrostatic force actuators can generate sufficiently strong vibration forces. Therefore, in this study, we propose a thin electrostatic resonant actuator (ERA) with significantly increased vibration force while maintaining a thin form factor by utilizing the characteristics of the electrostatic driving mechanism for applying large TSDs. The proposed thin ERA is designed to directly support the TSDs at the four corners in order to transmit strong vibrations to the touch surface of the large TSDs. The proposed thin ERA consists of an electrically grounded mass and electrodes spaced apart by a spacer. When a high-voltage signal is applied to the electrode, the coupling capacitance is charged between the electrode and the electrically grounded mass, and the mass moves toward the electrode by the generated electrostatic attraction, and when discharged, it returns to the equilibrium position by the restoring force of the leaf spring which is fabricated by wire-cutting the edge of elastic stainless-steel plate in a wave pattern.

Therefore, in an effort to develop vibrotactile actuators for large TSDs, this study proposes to design and test a thin electrostatic resonant actuator and apply it for a large touch panel. It intends (1) to design a thin ERA that can generate strong vibrotactile feedback by driving the mass connected to the leaf spring with a resonant frequency, (2) to evaluate the haptic performance of the developed prototype actuator, and (3) to develop the large haptic display system using the proposed actuator's array. In the next section, the driving mechanism of the electrostatic force actuator and the design and fabrication of the thin ERA with the controller are introduced. Then, the performance evaluation and its result of the developed prototype thin ERA are explained. Finally, the development of the large haptic display using the proposed actuator and its performance evaluation are explained.

2. Design of Thin ERA Module

This section presents the working principle of a vibrotactile actuator based on an electrostatic force mechanism and the design process of a thin ERA with the form factor of a flat plate. It also describes the fabricated ERA module and its controller. Finally, the performance evaluation and its results of the developed ERA module are explained.

2.1. Working Principle of the ERA Module. The design of the proposed ERA module strives to achieve a thin form factor while providing strong resonant vibration feedback using electrostatic force. Figure 1(a) shows an illustration of a simple electrostatic parallel plate actuator, consisting of the fixed electrode insulated by a dielectric film and a grounded mass with a spring. When a voltage is applied to the fixed

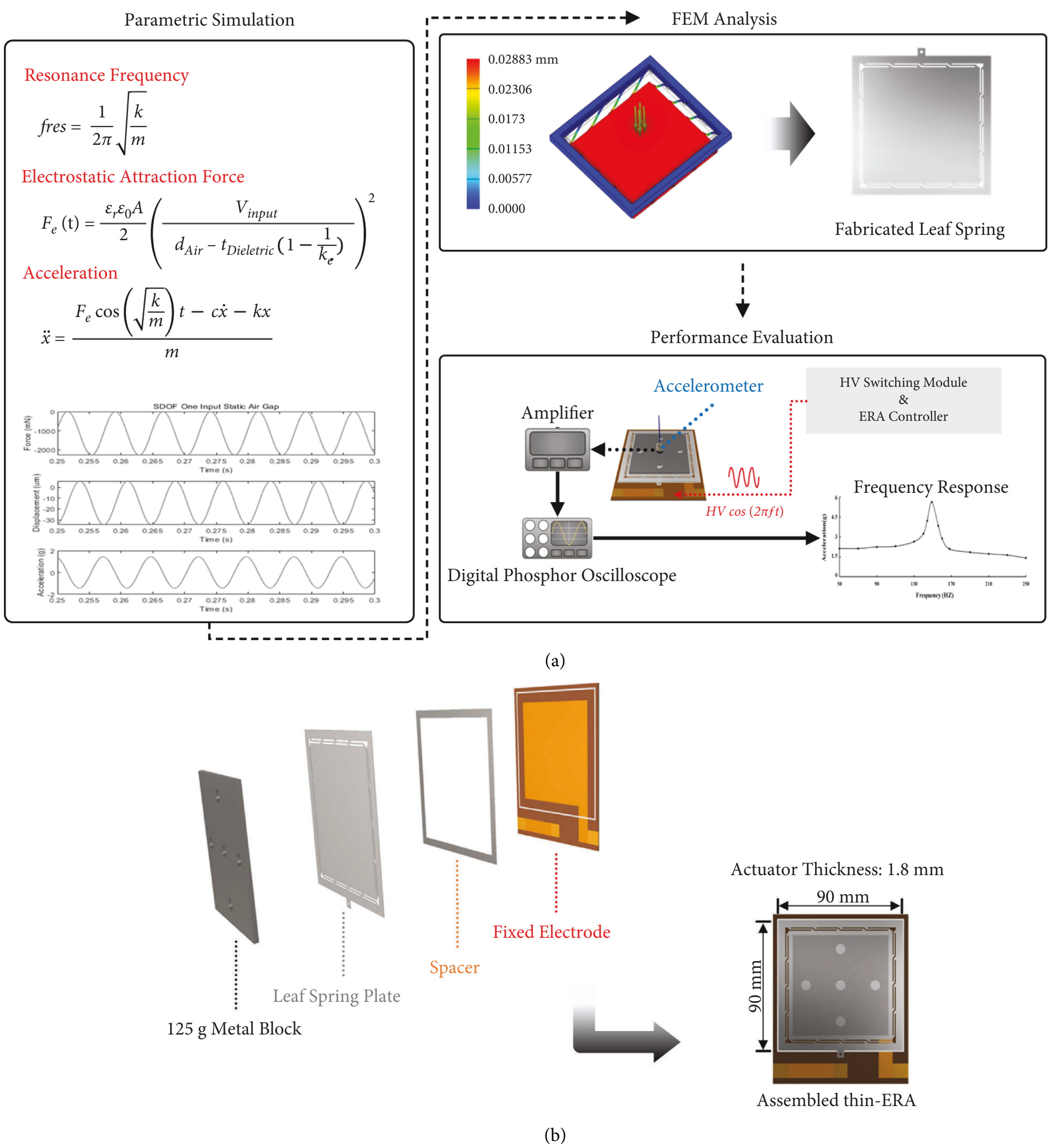


Figure 2: Development process of the proposed thin ERA: (a) Modeling design block diagram of leaf spring; (b) Exploded view of the proposed thin ERA.

electrode, an electric potential is induced between the grounded mass and the fixed electrode, generating electrostatic force. The interaction between the electrostatic force controlled by the input voltage and the spring force makes the grounded mass oscillate. The oscillatory motion of the mass can be used to create vibrotactile sensations. This electrostatic force actuation mechanism is employed in designing the proposed ERA module. Figure 1(b) shows an illustration of the proposed actuator where the movable mass is supported by leaf springs, rather than hanging it by a spring, enabling a thin actuator design by reducing the height of the actuator module. The working principle of the proposed ERA module is similar to that of the simple electrostatic parallel plate actuator. The oscillatory motion of the mass occurs when alternating high-voltage inputs are applied to the fixed electrode. The electrostatic force pulls on the mass when the high voltage is activated. When the voltage input is off, the coupling capacitance is discharged (the electrostatic force is removed), and in turn, the mass returns to the equilibrium position by the restoring force of the leaf spring. This process can be controlled depending on the frequency and amplitude of the voltage input signals. The intensity of the vibratory motion of the mass can be substantially amplified if it is derived at its resonant frequency.

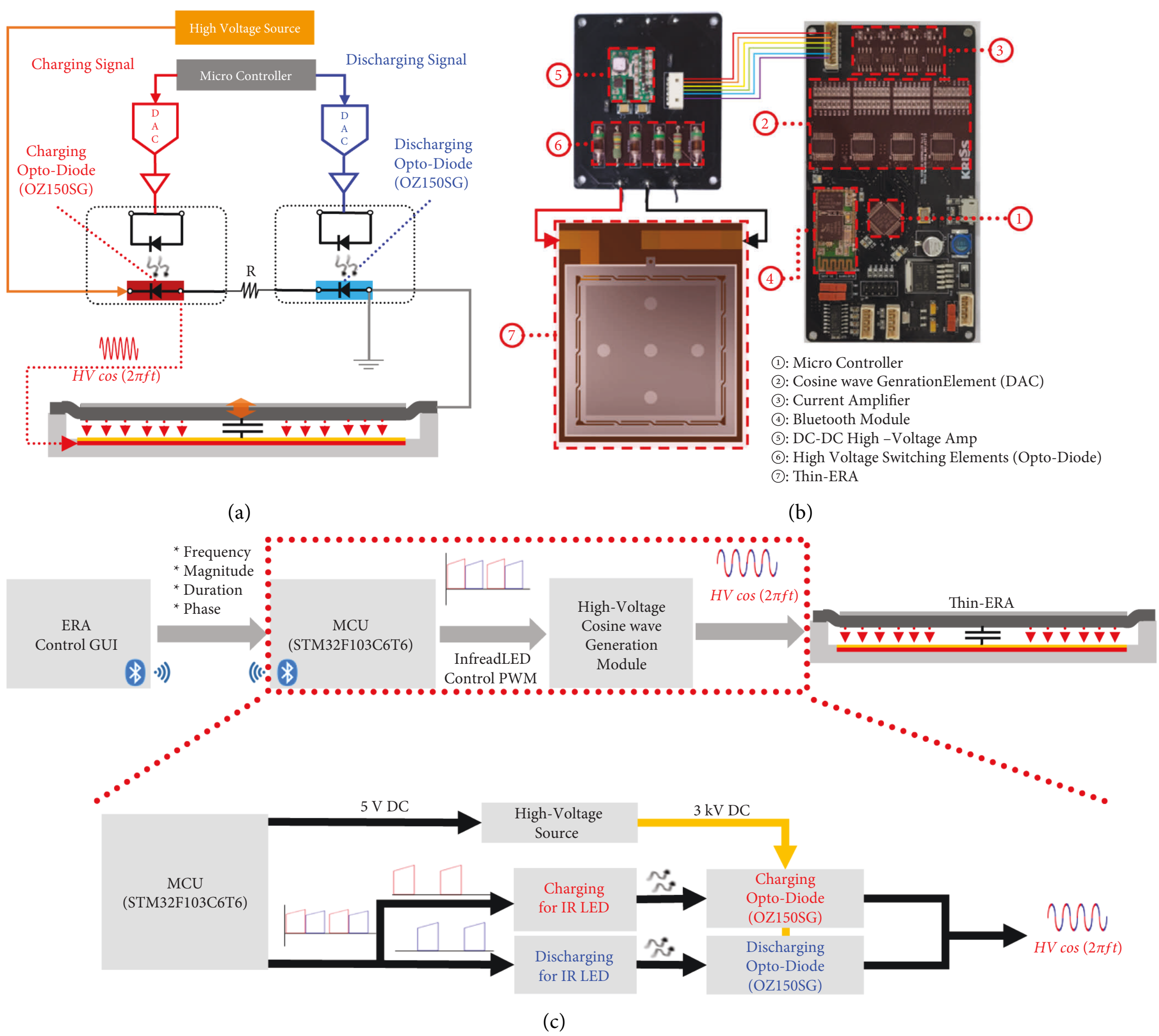


FIGURE 3: Development of thin ERA high-voltage switching controller: (a) A wiring diagram of the thin-ERA controller and the high-voltage generating module, (b) The fabricated thin-ERA controller and high-voltage generator connected to the ERA, (c) An operation block diagram of the thin-ERA module.

Equation (1) shows an expression for the electrostatic attraction force, $\mathbf{F_e}(\mathbf{t})$, between two insulated conductors [19].

$$\mathbf{F_e}(\mathbf{t}) = \frac{\boldsymbol{\varepsilon_r \varepsilon_0 A}}{\mathbf{2}} \left(\frac{V_{\mathbf{input}}}{d_{\mathbf{Air}} - t_{\mathbf{Dieletric}} \left(\mathbf{1} - (\mathbf{1}/\mathbf{k_e}) \right)} \right)^{\mathbf{2}}, \quad (1)$$

where ε_r is the relative permittivity of air, ε_0 is the vacuum permittivity, $\mathbf{A}$ is the electrode area, $\mathbf{V_{input}}$ is the input voltage, $\mathbf{d_{Air}}$ is air gap thickness, $\mathbf{t_{Dieletric}}$ is the insulating film thickness, and $\mathbf{k_e}$ is the relative permittivity of the insulating film. The grounded mass is pulled toward the fixed electrode by the attractive force and moves downward, and when the charged capacitance is discharged, the grounded mass returns to the original position by the elastic returning force of the spring.

2.2. Design and Fabrication of Thin ERA Module. Figure 2 shows an overall process of the design, fabrication, and evaluation of the proposed ERA module. This study intends to design a thin ERA module for a single-degree-of-freedom (SDOF) haptic interface system where a 500 g touch display is supported by four of the ERAs. To this end, it first performed a simulation study using an SDOF spring-mass system to identify the spring constant of the actuator that can produce at least 2 g at its resonant frequency of 130 Hz. These target values are selected because the Pacinian corpuscle of mechanoreceptor in human skin responds most sensitively to frequencies in the range of 80 Hz to 200 Hz, and the minimum threshold for vibration detection is more than 0.05 g [21, 22]. Based on the simulation study, the actuator is designed to have a spring stiffness of 70 kN/m when driven at a resonant frequency of 130 Hz with a grounded mass of 125 g. After the simulation study, the actual spring was modelled using finite element (FE) analysis. According to the FE analysis, the dimensions of 16 leaf springs around the square plate were determined to provide a proper stiffness of the actuator.

Figure 2(b) shows a fabricated assembly of the ERA prototype with components. As shown in the figure, the prototype consists of a thin spring plate with the dimension of 90 mm (width) × 90 mm (length) × 0.5 mm (thickness), a

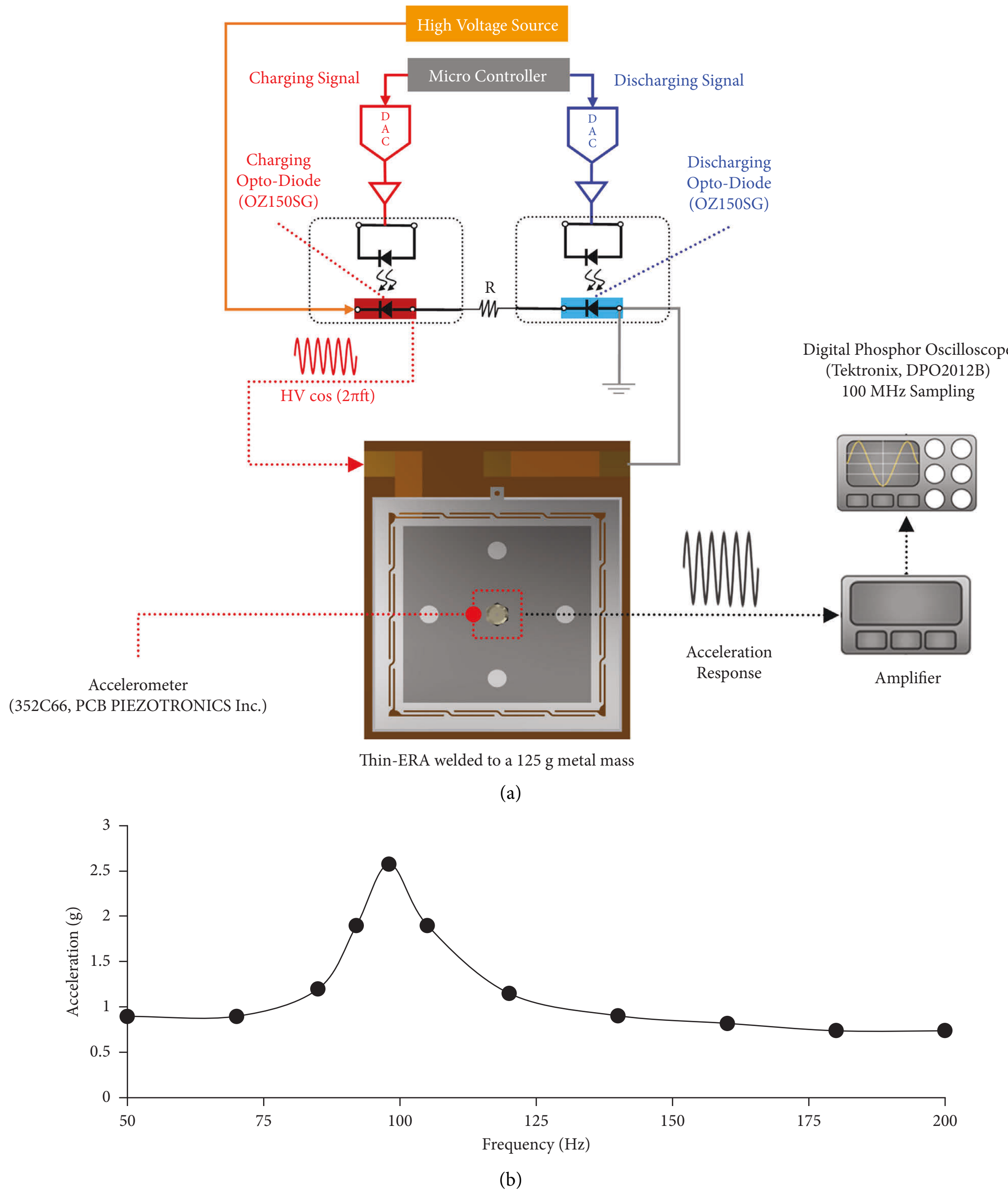
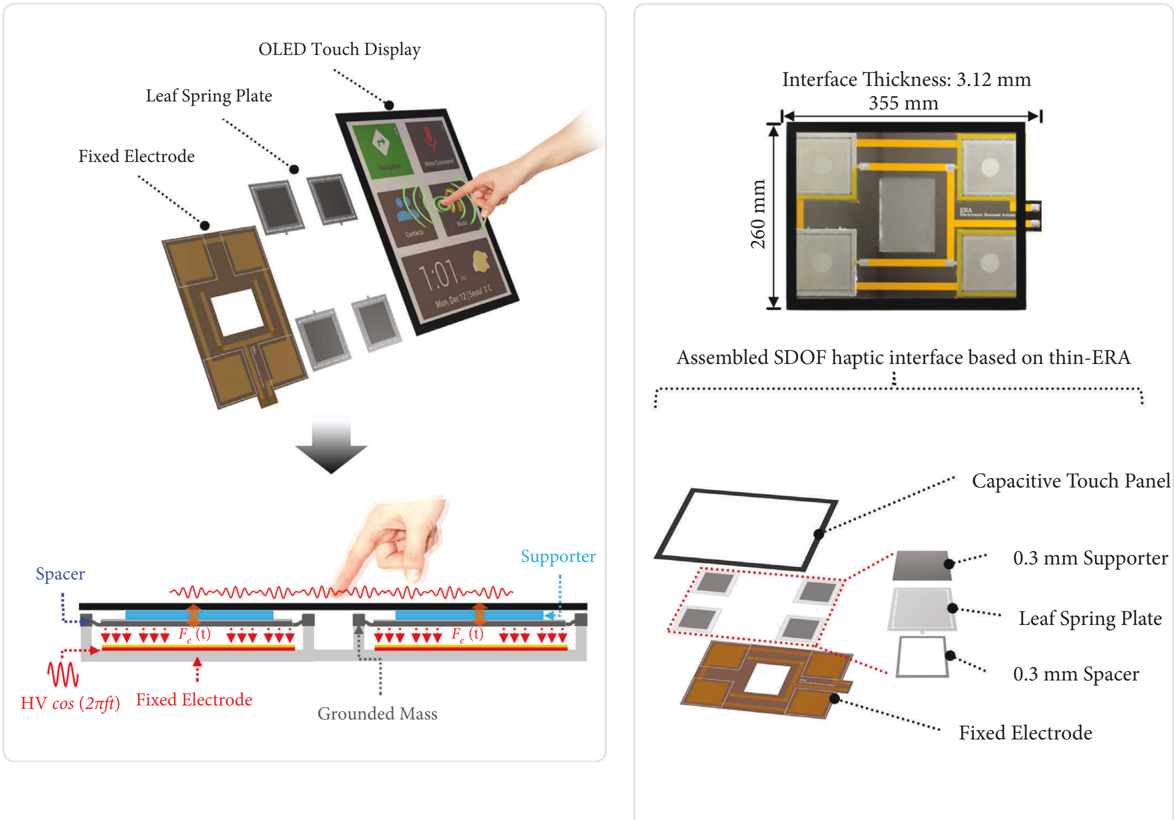


FIGURE 4: Performance evaluation of the ERA prototype: (a) An illustration of the test setup with the prototype ERA, (b) The acceleration response of the ERA with varying input frequencies.

3 mm-thick spacer, and an electrode insulated with a thin polyimide film. A metal block of 125 g is attached to the spring plate, which makes the overall thickness of the ERA module 1.8 mm. This prototype is experimentally evaluated using high-voltage inputs, as shown in Figure 2(a). The details of the testing and results are presented in the subsequent sections.

2.3. Development of a Controller for the ERA Module. Figure 3 shows the high-voltage input controller for the ERA along with its controller diagram and architecture. The controller module is designed to adjust the frequency, amplitude, and duration of the high-voltage signal to the ERA so that it can generate various vibrotactile patterns. As shown in Figure 3(b), the main components of the controller module include a microprocessor (Arm Coretex-M3, STM32F103C6T6) that generates a driving signal for the actuator, a small DC-DC converter capable of amplifying 5 V to 2.5 kV, and high-voltage switching modules that generate a high-voltage cosine signal for charging and discharging the capacitance. Figure 3(c) is a block diagram for controlling the ERA module. The user can select desired input parameters, such as the frequency and the amplitude, using the graphic user interface (GUI) in a tablet. The input



(a) (b)

Figure 5: Design and fabrication of haptic interface based on thin ERA: (a) Principle of operation of SDOF haptic interface based on thin ERA, (b) An exploded view of the fabricated haptic interface system based on thin ERA.

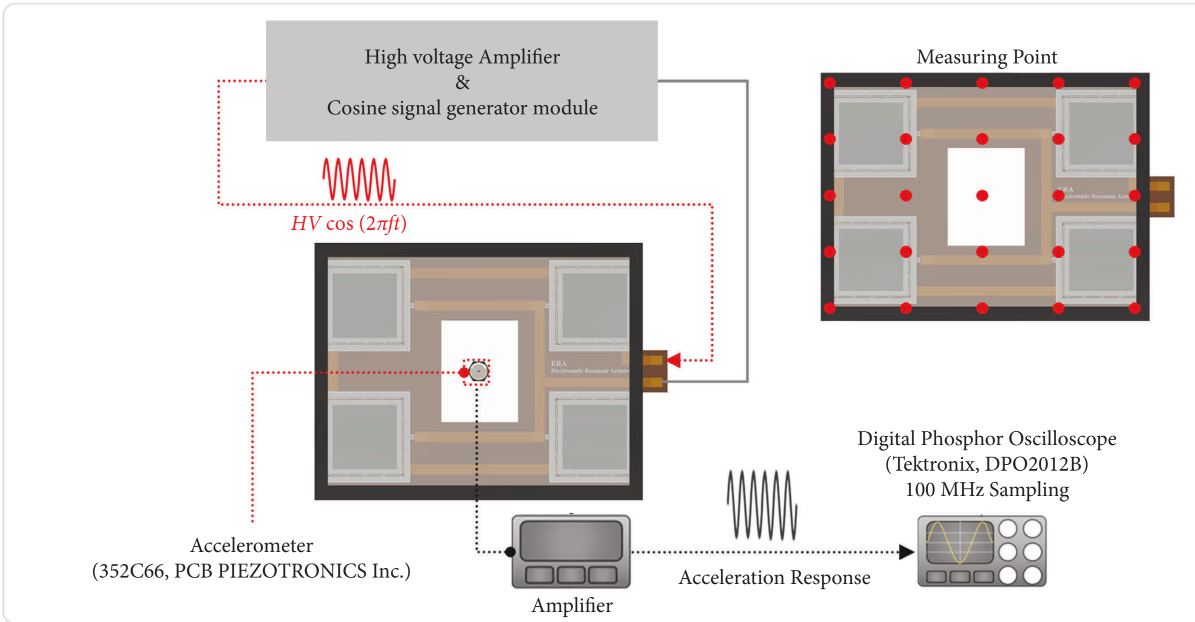
information is transmitted to the microprocessor control unit (MCU) through the wireless connection using Bluetooth between the ERA control GUI and MCU. The controller then generates a PWM signal for charging and discharging based on the information, and the current amplifier and infrared control the amount of infrared radiation of the LED using Opto diodes (OZ150SG), which drives the ERA. The fabricated controller and high-voltage signal generation module are shown in Figure 3(b).

3. Experimental Evaluation of the ERA Module and Its Application

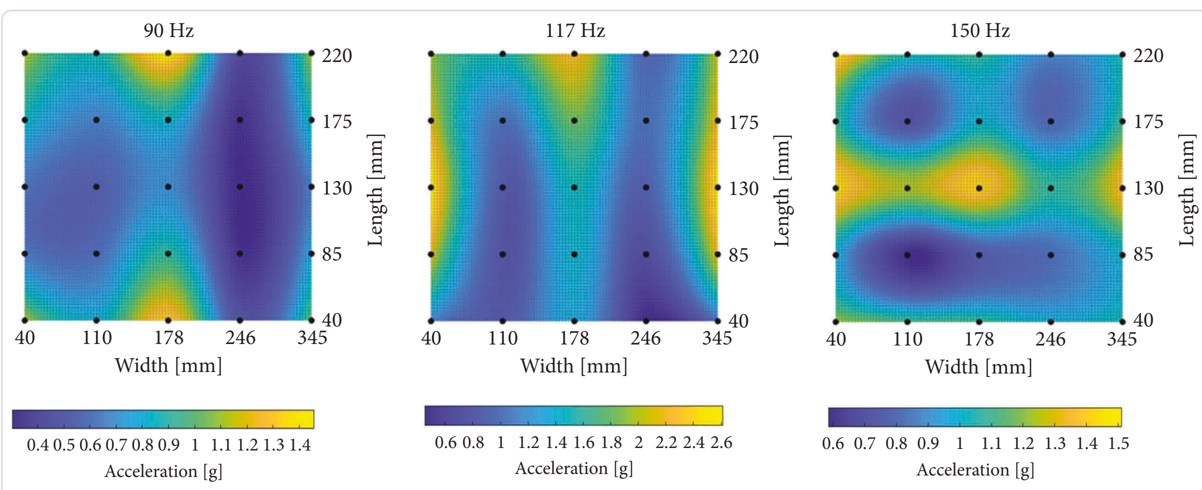
This section presents the experimental evaluation of the ERA module as well as its application for a larger TSD. Using the fabricated ERA prototype and the controller module, the performance of the system is evaluated to assess the acceleration responses of the prototype. Followed by the single module testing, a SDOF haptic interface system, consisting of a 17-inch display and four ERAs, was created and tested in order to study a feasibility of the ERA for a large TSD application.

3.1. Experimental Evaluation of the ERA Module. Figure 4(a) illustrates a single ERA module prototype testing setup. A 125 g metal block is attached to the ERA to simulate the mass of a touch display. Note that four ERA will be applied to a touch display whose mass is 500 g, so each ERA would support 125 g. To measure the acceleration response of the fabricated ERA prototype, an accelerometer (352C66, PCB PIEZOTRONICS Inc.) was placed on the top surface of the ERA. To evaluate the performance of the actuator, the control input signal with a frequency ranging from 50 Hz to 200 Hz was used. A digital oscilloscope (Tektronix, DPO2021B, Sampling Rate: 100 MHz) with a built-in DAQ function was used to collect the acceleration response.

Figure 4(b) shows how the peak acceleration of the ERA changes as the input frequency varies discretely. The results show that the maximum acceleration of up to 2.5 g was generated at the resonance frequency of 99 Hz. This resonant frequency is lower than the targeted resonant frequency of 130 Hz in the simulation study. The fabrication thin spring seems to cause the discrepancy between the experimental and simulation resonant frequencies. The study employed a wire-cutting technology to cut out slots in a thin metal sheet to create the spring. This delicate cutting process with the heat involved might have affected the property of the thin and narrow legs of the spring. Nonetheless, the resonance frequency still falls within the frequency range of 80 Hz to 200 Hz, which responds most sensitively to the mechanoreceptors of human skin, and the vibration force is generated 50 times greater than the minimum detection threshold of



(a)



(b)

Figure 6: Evaluation of the ERA-based haptic interface system: (a) Experimental setup and acceleration measurement points. (b) Colormaps for experimental results for three driving frequencies (90 Hz, 117 Hz, and 150 Hz).

0.05 g [22, 23]. Therefore, the results indicate that the prototype ERA can offer sufficiently strong vibrotactile feedback at a desired frequency range for a medium to large TSDs.

3.2. Experimental Evaluation of a Haptic Interface System. One of the goals of this study is to investigate a feasibility of the proposed ERAs for a large touch display application. To this end, this study designed and fabricated a haptic interface system using multiple ERA modules. Figure 5(a) shows a conceptual design of a thin haptic interface system where multiple ERA modules are attached to the back of the OLED (organic light emitting diode) touch panel in order to directly transmit vibrations created by one or more of the ERAs. Mobile devices generally create vibrations using an embedded actuator at a fixed location, so the vibrotactile sensations are indirectly conveyed to the user's fingertip. However, for the current interface design, the actuators directly excite the touch panel, and it can transmit the strongest possible vibrations for given actuators. In this study, a prototype haptic interface system is constructed using a 17-inch touch panel and four ERAs. As shown in the exploded view of the system in Figure 5(b), the haptic interface system consists of a 17-inch capacitive touch screen panel, four supporters of 0.3 mm thick, one spacer of 0.3 mm thick, four ERAs (leaf spring plate of 0.5 mm thick), and a fixed electrode. The four supporters are placed between the back of the touch panel and the ERA. Bonded on the edge of the printed circuit board (electrodes), the spacer provides the rattle space for the ERAs to move. The picture of an assembled haptic interface module is shown on top of Figure 5(b). The dimension of the module is 260 mm (width) × 355 mm (length) × 3.12 mm (thickness), and the total area of the fixed electrode is 5625 mm^2.

To evaluate the performance of the haptic interface module, this study presents selective cases with three distinct input frequencies (90 Hz, 117 Hz, and 150 Hz) within the most sensitive vibration range to human skin. An accelerometer (352C66, PCB PIEZOTRONICS Inc.) is used to measure the response of the panel in multiple locations. Figure 6(a) shows the 25 measurement points. The data were collected using a digital phosphor oscilloscope (Tektronix, DPO2021B). In this study, the four ERAs were operated simultaneously by the input control signal considering the bending modes of the rectangular panel. In other words, the ERAs are connected, and they are working concurrently with a single voltage input. In a future study, electrodes can be redesigned such that each of the ERAs can be controlled independently.

Figure 6(b) shows surface plots with a colormap that visualizes acceleration response values measured at the 25 measure points for each of the driving frequencies. For the 90 Hz input case, the maximum acceleration is 1.4 g at the middle of the top and the bottom edges of the panel. The peak acceleration of 2.6 g occurs at the middle of the left and the right edges of the panel when the ERAs are operated at 117 Hz. Unlike the other two cases, the maximum acceleration (1.5 g) takes place at the center of the panel for the 150 Hz input. In addition to the variations of the peak accelerations, the colormaps show that the overall distribution of the acceleration magnitudes across the panel varies depending on the frequency input. These results show a feasibility of using the proposed thin ERA modules that can be applied to large TSD applications.

4. Conclusion

The paper has presented the design and testing of a thin electrostatic resonant actuator and its application for large touch displays. The ERAs are intended to provide vibrotactile feedback to a medium or large-sized touch screen displays (TSDs) while keeping the device as thin as possible. The proposed ERA is designed to have an electrically grounded mass supported by the leaf spring to make it slim and vibrate based on the electrostatic attraction force that interacts with the elastic restoring force. It is designed to produce the maximum oscillatory motion at its resonant frequency; hence, it is named as electrostatic resonant actuator or ERA. A prototype ERA was constructed using a simulation study and a FE analysis. After adding a mass that represents a fraction of a TSD mass to the ERA prototype, it was tested with a harmonic input signal with a varying input frequency. The test results show that the maximum acceleration of 2.5 g was generated at the resonant frequency, indicating that the ERA can produce sufficiently large vibration sensations. Followed by the characterization testing of the ERA prototype itself, this study constructed a haptic interface system in order to investigate a feasibility of ERAs for large display applications. For the haptic interface system, a 17-inch capacitive touch panel is supported by four ERAs at its four corners, and they directly transmit vibrations to the panel. The four ERAs were wired such that they act like a single actuator working simultaneously. Using selective inputs with three different driving frequencies, the performance of the haptic interface system was evaluated. The acceleration response of the panel was measured at 25 different positions on the panel. The results show that the magnitude of accelerations varied across the panel with peak accelerations up to 2.6 g, which is sufficiently large to be perceived by fingertips, for the three input frequencies considered in the study. Thus, the proposed ERAs are potentially useful for generating vibrotactile feedback for mid-to-large touch displays as well as virtual reality-based wearable devices in the future [23]. The future work will focus on a more extensive evaluation of multiple ERAs for large TSD applications and developing controllers that are capable of controlling ERAs independently.

Data Availability

No data were used to support this study.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Authors' Contributions

Young-Min Kim and Tae-Heon Yang contributed equally to this paper.

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