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Novel linear impact-resonant actuator for mobile applications

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ABSTRACT

In this study, a novel linear impact-resonant actuator was proposed for mobile device applications. The most significant issue in mobile haptic actuators is the ability to provide various vibrotactile and alert functions despite their size and power consumption limitations. This study aimed to achieve fast and strong impact vibrations over a wide frequency range, including the resonant frequency, which decoupled the intensity and frequency of the vibration to achieve both fruitful vibrotactile feedback and strong alarming vibration. To accomplish this, a new mechanism was proposed that can amplify the impact force at the end of the stroke and increase the speed of the response. The magnetic flux path was optimized using an equivalent magnetic circuit model to maximize the electromagnetic force. The performance of a prototype actuator (11 mm × 9 mm × 3.2 mm) was evaluated in terms of the response time and vibration acceleration amplitude under an input power of 0.3 W. The experimental results clearly showed that the proposed actuator could create a vibration acceleration that was greater than 2 g over a frequency range of 1–210 Hz with a fast response of 4 ms and extremely short residual vibration. In addition, a stronger impact force of around 3 g could be generated near the resonant frequency of 190 Hz.

1. Introduction

Research on haptic technology that can effectively present a sense of touch is accelerating in response to the increasing demand from users for new sensory information in human–computer interfaces, which have previously focused on visual and audio feedback. Since the sense of touch is an effective means of supporting communication, coupling visual or audio information with haptic feedback can increase the degree of realism and sense of immersion. Recently, the use of touchscreen technology in portable consumer electronic products has grown dramatically, not only to visually provide a variety of information through graphical images, but also to manipulate objects directly by touching and dragging with a user's fingers [1]. As these displays have become larger, various haptic feedback methods that can play roles in making the presentation of information richer and more expressive have been required, beyond the simple function to draw the user's attention to an incoming call or message. In addition, the haptic interaction between the user and the device has become more important, because the virtual soft keyboard of a touchscreen cannot provide the natural tactile feedback of real physical buttons [2]. The importance of tactile feedback has already been recognized in many fields, ranging from the design of handheld interfaces such as mobile devices to virtual reality applications. Hoggan et al. showed that mobile touchscreen buttons with tactile feedback could provide usability close to that of a real physical keyboard and improve the performance of fingertip interaction to achieve text entry with fewer errors and greater speeds. Tactile feedback on a touchscreen is also useful when using the stylus [3,4]. It is also attractive because the sense of touch is a private modality that allows unobtrusive interaction [5]. Brown et al. showed that structured vibrotactile messages alone could be used for communicating information without auditory and visual feedback [6,7]. In most mobile devices, vibrotactile feedback has commonly been provided to create haptic effects because vibration can quickly convey a strong stimulation to a human with low power consumption, while minimizing the design space [8,9]. Numerous vibrotactile actuators have been developed to make the best use of haptic feedback. However, there are physical constraints to their use in mobile devices. Because the newest mobile devices are lighter and thinner, such mobile actuators should also be lightweight and small, especially in the thickness dimension, to allow them to be incorporated into devices. Moreover, they should provide sufficient force with a low driving voltage and power consumption. In addition, when developing vibrotactile actuators, human factors should be considered when utilizing vibration parameters such as the frequency, intensity, waveform, and duration used to provide tactile information. There have been various psychophysical studies to

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understand the effects of vibration properties on human perception. The mechanoreceptors distributed with a high innervation density in human fingertips, which are the body parts most commonly used to interact with a touchscreen, can be activated by a vibrotactile stimulus in response to the frequency, amplitude, and waveform of the vibration. Because the four major mechanoreceptors (merkel disks, ruffini corpuscles, meissner corpuscles, and pacinian corpuscles) in the skin have individual functions and sensitive frequency domains, it is advantageous for an actuator to stimulate all of them by operating in a wide frequency range to encode a variety of tactile information [10–12]. In addition, the ability to generate a greater force with the actuator makes it possible to present a larger quantity of haptic information because a human can perceive changes in vibration intensity [13,14]. Being able to generate a sufficient vibration intensity over a wide frequency domain and control the frequency and amplitude independently, with different durations and repetition rates, makes possible an extremely large variety of tactile patterns [2,15]. Finally, a fast actuator response should be supported in order to deliver haptic information accurately and efficiently to users. Because the sense of touch can perceive two successive stimuli in only 5 ms, which is faster than the sense of vision, the ideal actuator should have a response faster than 5 ms. Moreover, to convey the desired haptic signals in rapid succession, there should be no residual vibration. When entering numbers or text on a touchscreen's virtual keypad, users feel that the sensation is more comfortable and natural when the tactile feedback is rapid, whereas they feel that the tactile feedback is rather disturbing and more errors occur when there is latency [16].

The eccentric rotary motor that is widely used in mobile devices utilizes the centrifugal force of an unbalanced mass. However, the amplitude of the vibration is coupled with the frequency, and its slow response time (more than 100 ms) and long residual vibration by inertia make it difficult to provide fast haptic feedback. As a result, it is unable to encode a complex vibration pattern and is limited to generating a silent alarm by continuous vibration. Fukumoto et al. proposed a voice coil-type linear vibrotactile actuator to improve the response rate. The linear motion of the mass not only improves the response of the actuator but also decouples the amplitude and frequency of the vibration [17]. However, the response rate of a commercial linear resonant actuator (LRA) is still not fast (about 20 ms), and it is difficult to generate a sharp effect such as the sensation of pressing a button because of the long residual vibration. In contrast, to reproduce a realistic button sensation by means of vibration, it is necessary to generate a sharp vibration with fast rising and falling times [18]. Moreover, it can generate sufficient force only at a fixed frequency (the resonant frequency), which cannot provide numerous vibrotactile sensations. For example, C2 Tactor from Engineering Acoustics Inc. has a resonant frequency of 250 Hz [3,19]. Various actuators have been developed to overcome the limitations of the LRA. TouchEngine, which is constructed of multiple layers of thin piezoceramic films, enables the independent control of the amplitude and frequency of the vibration, providing localized tactile feedback to a touchscreen in a wide frequency range, with fast acceleration. However, its driving voltage is quite high (8–10 V) [20]. The force reactor from Alps Electric Co. can generate impact vibration in a broad range of frequencies. Its rapid response and only slight residual vibration after impact vibration is appropriate to encode a variety of haptic information, including physical button sensations. Although its s-type force reactor is small enough to be mounted in mobile devices, its vibration amplitude (0.8 G) is too weak to convey sufficient force. Yang et al. developed a subminiature impact actuator operating in the range of 1–100 Hz using an unstable structure. However, it does not work at frequencies near 250 Hz, where humans are the most sensitive to vibration. In addition, its power consumption is quite high (0.6 W), and a structurally unnecessary axial force occurs [21]. Although many actuators have already been developed, additional studies need to be conducted to develop high-performance haptic actuators for mobile devices.

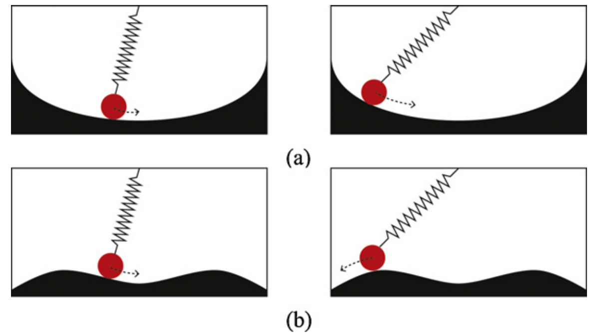

Fig. 1. Metaphors of magnetic systems: (a) linear resonant actuator and (b) linear impact resonant actuator.

This paper proposes a novel linear impact resonant actuator (LIRA) to overcome the limitations of conventional vibrotactile mobile actuators. It adopts a new mechanism that can generate a fast and strong impact force at the end of the stroke over a wide frequency range, including the resonant frequency. The next section describes the operating principle of the LIRA, which uses an electromagnetic force. The LIRA was optimized using a magnetic circuit model and refined using a finite element magnetic analysis. After a prototype of the LIRA was implemented, its performance characteristics, including its response time and vibration acceleration amplitude, were identified in experiments. The experimental results showed that the proposed actuator was capable of providing an abundance of haptic patterns and operated in a wide working frequency range with fast responsiveness and low power consumption.

2. Design and operating principle

The characteristics of the magnetic systems for the LRA and LIRA are described using metaphors in Fig. 1, considering that no electromagnetic force is applied to the actuator. In the case of the LRA, the elastic restoring force of the spring is stronger than the magnetic force of the permanent magnet (PM) over the entire range of the mass' motion. Therefore, it is difficult for a strong attraction to occur in the air gap, which can cause a strong impact force at the end of the stroke, even if an electromagnetic force is applied. The mass of the LRA can be compared to a ball hanging from an elastic spring and resting on a concave surface, as shown in Fig. 1(a). The ball always returns to its original equilibrium position after a perturbation. In this structure, it is difficult to generate a strong impact force at both ends, even if an external force is applied, because of the system characteristics. On the other hand, the magnetic system of the LIRA was designed so that the magnetic force of the PM is stronger than the elastic restoring force of the spring near both ends. Therefore, a strong attraction can occur at the end of the stroke, which produces a strong impact force when an electromagnetic force is applied. The structure of Fig. 1(b) describes the characteristics of the LIRA. If the ball is located between the convex surfaces, then it goes back to its equilibrium position. However, when the ball is located beyond the convex surfaces, it moves in the opposite direction from the equilibrium position. Eventually, the ball creates an impact vibration by bumping into a wall. A convex surface indicates a location where the magnetic force of the PM begins to be stronger than the elastic restoring force of the spring. These characteristics will be discussed in detail in section 4. Because just a single impulse can produce a fast and strong impact vibration, it is appro-