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Measurement of the Strain Behavior Inside the Skin under Edge Stimulation Condition

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Abstract: We have reported the edge stimulation (ES) method that use multiple vibrations in different phases and generate a sharp tactile sensation at the boundary of the vibrations. Through a 2D finite element deformation analysis on a finger model, we reported a non-linear behavior of a finger skin deformation against vibratory stimulus that generates high frequency components of the skin strain. Not only the increase in strain inside the skin, but also the generation of high frequency enables human to perceive stronger tactile sensations that helps efficient tactile feedbacks. In this study, to verify the generation of high frequency under certain boundary condition, we develop strain gages embedded skin model sensor that consists of three layers representing human skin's structure and measure the spatio-temporal behaviors of strain inside the skin. According to the spectral analysis result of the sensor's output, the amplitude of main frequency was weaken and the high frequency component accounted for a larger percentage at the edge compared to the other area. However an obvious increase in high frequency that we expected to occur was not observed on this skin sensor. A 3D finite element deformation analysis was then conducted on a skin sensor model to observe the time variant boundary conditions in detail. The analysis result demonstrated the generation of high frequency component locally between the vibrations and we discussed the skin's non-linear filtering effect against the input vibratory stimulus.

Keywords: Tactile Sensor, Vibrotactile Stimulation

1. INTRODUCTION

The proliferation of limited-power/space mobile devices equipped with touch panels has greatly increased the demand for efficient haptic feedback. Tactile feedback are generally produced by vibratory stimuli, to which humans are highly sensitive. This is known as vibrotactile stimulation, the applications of which include mobile devices' vibration alarm. We have been reported Edge Stimulation (ES) method [1] with which situation greatly enhances human vibrotactile sensitivity and enables to perceive 5 μm at 30 Hz vibration, even though they normally require a 30 μm amplitude. Fig. 1 shows the schematic of ES method. One perceives strong tactile sensation between the edges of two surfaces that vibrate in different phases. The gap distance of two vibratory surfaces should be small and the height gap should be zero for the better enhancement. Throughout the skin model finite element deformation analysis of our previous study, the generation of high frequency component of skin strain was discovered. This was observed locally around the gap of two vibratory surfaces while whole skin was vibrating in the same frequency to vibratory surface. Since human is sensitive to higher frequency (in range of 0-300 Hz), this phenomenon can be the key for the enhancement of ES method.

In this study, to verify the generation of high frequency strain, we develop a skin model sensor embedding five strain gages spatially distributed. We developed the measuring system representing ES condition using two independent vibratory surfaces. We measure the spatio-temporal strain behavior inside the skin under ES condition using the skin sensor. Also 3D finite element deformation analysis is conducted to observe the detail skin deformation and the changes of skin-surface boundary conditions around the gap. According to the measurement and analysis result, we discuss the reason for the generation of high frequency strain under ES condition.

† Tatsuma Sakurai is the presenter of this paper.

2. SKIN SENSOR

A skin sensor needs to have soft tissue layer structure and capable for measuring the spatio-temporal distribution of skin strain. Our skin sensor consists of three layers; the first layer represents epidermis/dermis (0.0-1.0 mm deep), the second layer represents subcutis (1.0-8.0 mm), and the last layer (8.0-12.0 mm) represented the bone. The first layer was created by urethane resin (Exseal Hitohada gel) which was elastic modulus of 5.2 kgf/cm ^{2} and the second layer was 1.2 kgf/cm ^{2}. The last layer was rigid acrylic plate representing a bone. The structure, the material properties and the method of the construction of the sensor were referenced from Maeno's study that analyzed the spatial distribution inside a finger sliding on a plate[2]. Fig. 2 (a), (b) shows the horizontal and vertical location of the strain gages. Five strain gages were embedded between the first and the second layers where the FA I and SA I receptors exist. The gages were attached on the membrane of the first layer and measured the spatial distribution of skin strain in 1.0 mm resolution. The output signals of the sensor were amped by an amplifier (San.ei STRAIN AMPLIFIER 6M82).

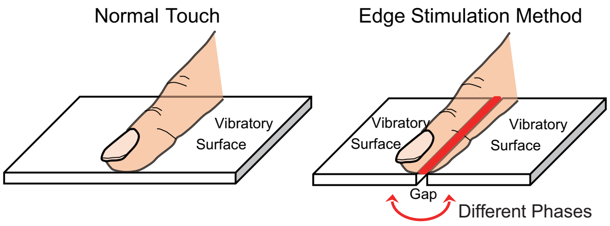

Fig. 1 Schematic of edge stimulation method. Two plain flat surfaces of vibrators in close proximity vibrate in different phases.

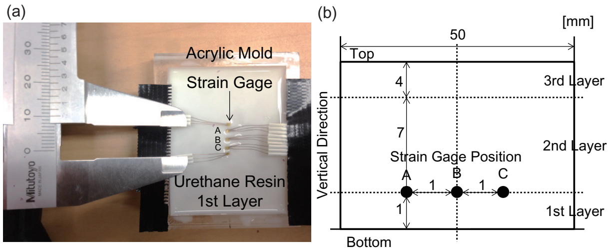

Fig. 2 Skin sensor. (a). Horizontal location of strain gages. (b). Cross section sketch of the skin sensor.

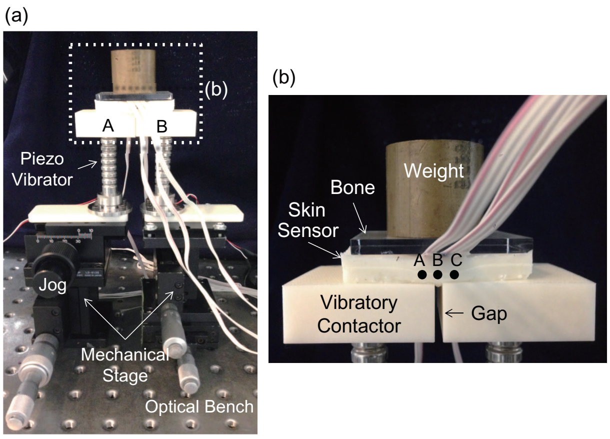

Fig. 3 Skin model sensor. (a). Whole experimental system. (b). Conditions around the skin sensor.

3. EXPERIMENT

The objective of this measurement is to observe the spatio-temporal behavior of strain inside the skin. We expect high frequency component of strain, the non-linear frequency component, is observed at the gap.

3.1. Experimental Setup

Fig. 3 (a), (b)shows the experimental setup. A mechanical stage with a precision of 0.1 mm and a rigid stage were located on a base with sufficient area and weight. Two piezoelectric actuators (TOKIN, AHB850C851FPOL-1F) were placed on these stages. These vibrators can provide amplitudes of more than 85 μ m, and the response frequency is greater than 400 Hz. By tuning a jog of the mechanical stage, the gap distance and the height can be easily changed. Then skin sensor was placed on the center of two vibrators' contactors with 100 g weight representing 1 N indentation force.

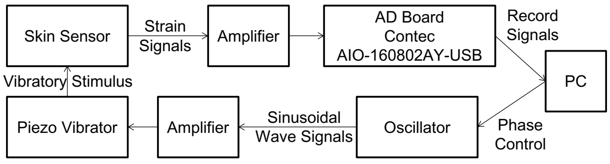

Fig. 4 System of the measurement.

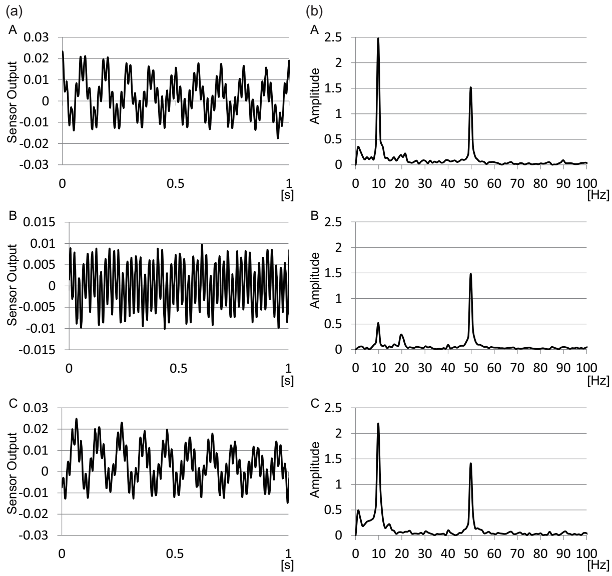

Fig. 5 Experimental results. (a). Skin sensor output at each strain gage position. (b). Spectral amplitude of each signal.

3.2. Method

The vibrators were actuated by the following equation:

$$VibratorA : f(t) = A\sin(2\pi ft) \quad (1)$$

$$VibratorB : g(t) = A\sin(2\pi ft + \pi) \quad (2)$$

where $f(t)$ and $g(t)$ are the displacement [μm], A is the amplitude [μm] and f is the frequency [Hz]. Frequency was set to 10 Hz and amplitudes to 20 μm and the gap distance was set to 0.5 mm. The system of measurement is shown in Fig. 4.

3.3. Result

Fig. 5 shows the sensor output signals and the result of their spectral analysis. According to Fig. 5 (a), skin sensor's outputs followed the vibrator displacement at position A and C in Fig. 2 (b) while the strain behavior at position B did not. At position B, the amplitude of main frequency 10 Hz was weaken and the high frequency 20 Hz accounted for a large percentage compared to position A and C. However an obvious increase in high frequency that we expected to occur was not observed on this skin sensor. Position A and C, the signals had only linear frequency component and the spectral amplitude peak at 50 Hz were hum noise.

4. DEFORMATION ANALYSIS

According to the output of the skin sensor, the slight increase in high frequency strain was observed while the vibrators were vibrated in low frequency. The shift in

Table 1 Parameters of the model

Depth from Surface [mm]	Young's Modulus [MPa]	Poisson's Ratio -	Density [kg/mm ^{3}]
0.0-1.0	0.136	0.48	1.1e-6
0.1-0.8	0.085	0.48	1.1e-6

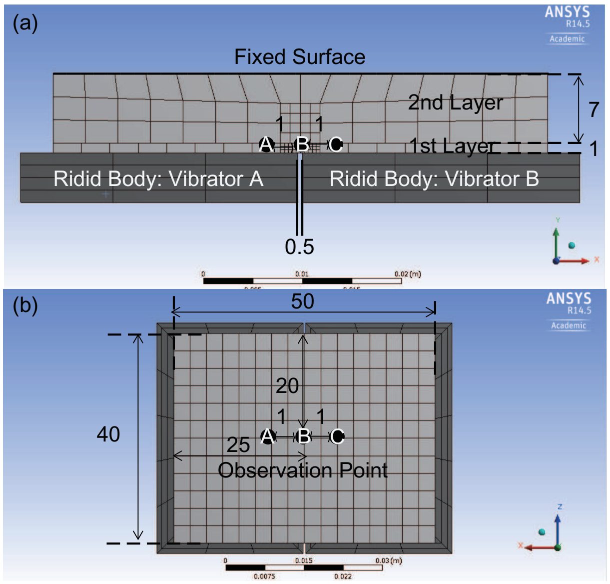

Fig. 6 Finite element skin model. (a). Front view. (b) Top view.

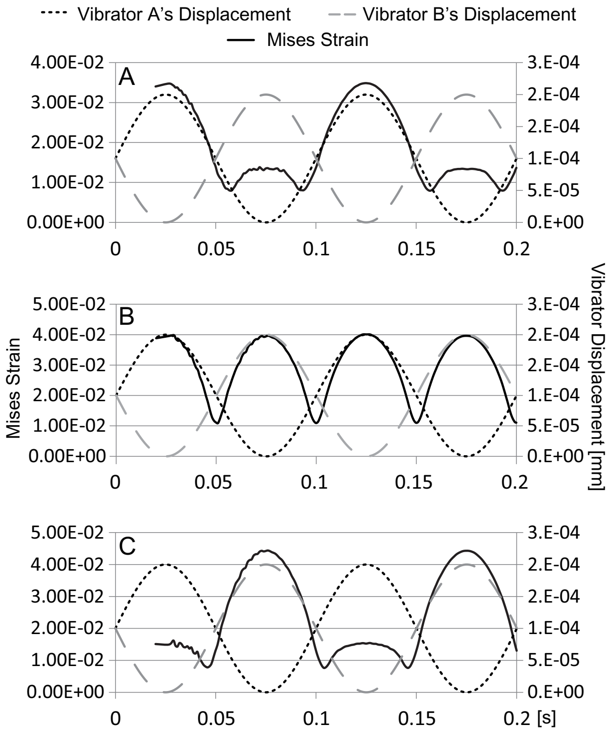

Fig. 7 Dynamic deformation analysis result. Black lines show the strain behavior at each point and dashed/dot lines show the vibrator displacement.

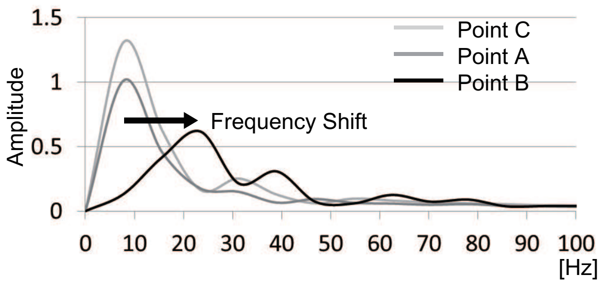

Fig. 8 Spectral analysis on the strain wave of analysis result. Point B has doubled frequency against the vibrator input 10 Hz.

the frequency suggests non-linear phenomena under ES condition. For the further observation, we conducted 3D finite element deformation analysis using a skin model.

4.1. Model

Fig. 6 shows the skin model developed for the simulation. The model size and other boundary conditions were made to be the same as the actual skin sensor of this study. The height of the model was 8.0 mm, the width was 50.0 mm and the depth was 40.0 mm. These dimensions were large enough to make the sides free from the boundary effects. The skin model was consists of two layers; the first layer represents epidermis/dermis (0.0-1.0 mm deep), the second layer represents subcutis (1.0-8.0 mm). The bone layer was substituted by a zero-displacement fixed surface at the top of the model. Mechanical properties of the model was taken from Maeno's[2] work as shown in Table. 1.

The smallest meshes were 0.3 mm and were used around the gap at the bottom of the model. There were two rigid surfaces at the bottom of the skin model.

4.2. Method

Vibrator surfaces were vibrated in the opposite phases according to e.q. (1) and (2). Amplitude was 0.1 mm and the frequency was 10 Hz. Both surfaces were in non-frictional contact with the model and the skin was able to peel off from them. The total analysis time was 0.2 s and the smallest time step was 0.001 s. We observed the Mises strain at the observation point A, B and C where the strain gage are embedded in the skin sensor, shown in Fig. 6. The points were 1 mm from the bottom just between the 1st and 2nd layer.

4.3. Result

Fig. 7 shows the Mises strain behaviors at each observation point. Dashed and dots lines are the vibrators' displacement for the reference of the frequency and the phases. At the observation point A and C, the Mises strain almost moved along the each vibrator's displacement. The waveforms seem to be half waves. At the observation point B, at the very center of the gap, the waveform was almost like full wave.

Fig. 8 shows the spectral analysis on the strain at each point. Point A and C mainly include 10 Hz component the same as vibrator input. In contrast, point B mainly includes 20 Hz which is double against the input frequency.

4.4. Discussion: Nonlinear Filtering Effect of ES method

Throughout the experiment, the superposition of opposite phased sinusoidal vibration under ES condition

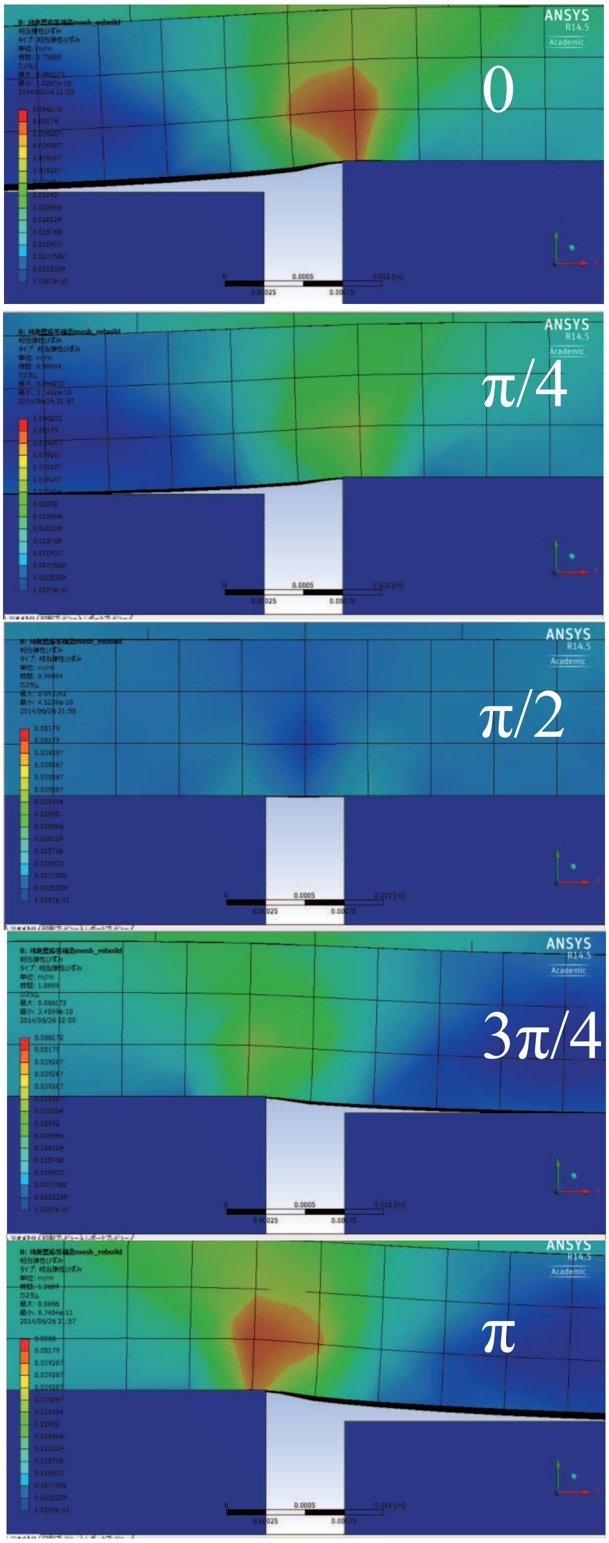

Fig. 9 Animation of dynamic analysis. Full-wave filtering effect is observed between the skin and the vibrators vibrating in opposite phases.

caused increase of strain at the edge and the generation of high frequency strain at the gap. Here, we have assumed the non-linear filtering effect for sinusoidal inputs under the ES condition, based on the result of the dynamic analysis that the high frequency was generated between the two surfaces in close proximity.

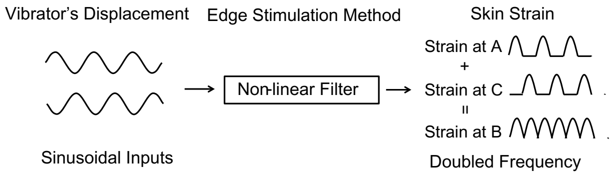

Fig. 10 Schematic of the ES non-linear filter.

Fig. 9 is an animation of dynamic deformation analysis. The skin moves along the envelope of the two vibrators in the gap. In other words, the ES condition can be considered to have a full-wave filtering effect. The strain increased at the edge of the right vibrating surface when it was raised, and at the contact boundary between the skin and the edge of the right vibrating surface. The same occurred on the right when the right vibrator was lowered. The sinusoidal inputs were transformed into non-linear strains of the skin owing to these time variant contact conditions. Fig. 10 is a schematic of ES's full wave-filtering effect. Though this situation could happen in actual skin as dynamic deformation analysis suggests, the skin model sensor did not observed the non-linear frequency very much.

5. CONCLUSION

We developed skin sensor to measure the spatio-temporal behavior of skin strain inside the finger. The spectral analysis of the sensor signals under ES method indicated the increase of strain at the edge and the slight increase in high frequency component of strain at the gap. The result of dynamic deformation analysis on finite element skin model indicated significant increase the amplitude of high frequency component with which we suggested non-linear(full-wave) filtering effect of ES method. The difference in the spectral output of strain between the deformation analysis and the skin sensor should be discussed in our future works. The effect of the other mechanical parameters for the high frequency, such as gap distance and indentation force, are also to be specified.

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