Finger Ring Tactile Interface Based on Propagating Elastic Waves on Human Fingers

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Abstract

We propose a new tactile device which measures several DOF vibrations propagating along the finger. The device can be used both as a tactile sensor and human-machine interface. In this paper, as a pilot experiment, we carried out experiments on the identification of contact positions by using 2 DOF vibrations. It was shown that with a 2-axis accelerometer placed on the backside of the proximal phalanx, tapping on distal phalanx and middle phalanx can be discriminated.

1. Introduction

When people attempt to obtain information regarding to the shape, textures, material, etc of objects by using tactile sensation, they rub their finger pads on the surface of the objects. The features of the surface of the objects are converted into mechanical vibrations to be sensed by mechanoreceptors. Unlike mechanical receptors which reside just under the finger pad, it is difficult to directly measure the vibrations excited on the finger pad without disturbing tactile perception. However, the induced vibrations propagate along the finger and they can be observed at distant positions from the finger pad.

We propose a new tactile interface which measures vibrations of several different modes at the proximal or middle phalanx. Fig. 1 shows a concept sketch of the device. The shape of the device is like a finger ring. The device measures the vibrations induced at the fingertip either by tapping or by rubbing textures on the finger pad.

Analogous to the seismology[1], by measuring several different modes of elastic waves, it is considered to be possible to estimate some properties on the source of the vibrations, such as the location of contact, the direction of applied force, etc. These properties are considered to convey a part of tactile information. For example, Kuchenbecker [2] proposed a haptic display which controls the location of contact and displays the shape of the objects.

Using a human finger as a part of tactile sensors is an attractive idea. Mascaro et al. have proposed a unique device which can estimate the fingertip touch forces and postures by measuring the coloration of the finger nails [3][4]. As they have pointed out, one of the merits of this sensor is that in using the device, it doesn't deteriorate the user's tactile feeling compared to placing force-sensing pads at the fingertips. The user can manipulate objects without haptic obstruction while the sensor can measure the equivalent information to the user's perception.

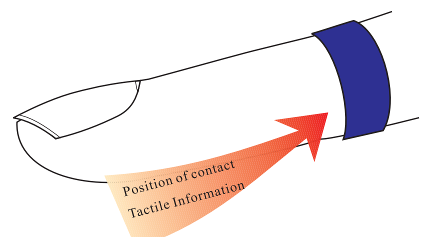

Fig. 1 A concept picture of the finger ring tactile interface. The device measures different modes of vibrations and obtains tactile information.

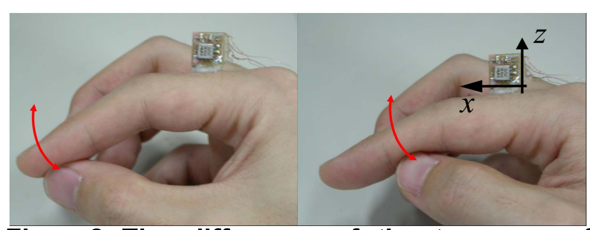

Fig. 2 The difference of the two way of tapping. The axis of the acceleration meter is also shown. Left: tapping on the distal phalanx (DP tapping) Right: tapping on the middle phalanx (MP tapping).

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In addition, using a human finger as a sensor probe is reasonable from the viewpoint of tactile sensing because mechanical properties of finger tissue play an important role in obtaining tactile information. Contrary to the auditory or visual sensation, tactile sensation requires mutual interaction between objects and skin. When an object is pushed onto the skin, the displacement of the object and that of the skin are determined depending on the compliance of both the skin and the object. Therefore, in designing tactile sensors equivalent to human tactile perception, the sensor probe should have the equal softness as the human skin. If a human finger is employed as a sensor probe, the mechanical properties of the sensor probe should be completely ideal.

Our device can be used not only as a tactile sensor but also as a human-machine interface. Fukumoto et al. [5][6] have proposed a device named "UbiButton." UbiButton can detect the vibration excited by finger tapping and interpret the rhythm and the number of tapping as input commands to the device. Our device can utilize not only the rhythm or the number of the taps but also the estimated location of contact. That means the device can assign "virtual buttons" located along the finger.

In this study, as the first stage of the development, a 2-axis accelerometer was used to measure vibrations along two different directions on the backside of the proximal phalanx. We show that by measuring 2 DOF vibrations, it is possible to discriminate tapping on the distal phalanx from tapping on the middle phalanx. In Section 2, the experimental procedure is described. Before discussing the results in Section 4, the methods and results of preliminary experiments are briefly described in Section 3.

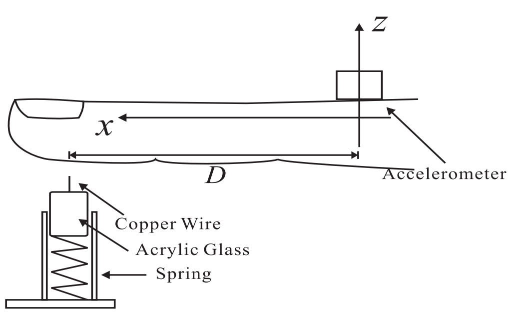

Fig. 3 A schematic drawing of the setup for preliminary experiments.

2. Methods

2.1. Device

In order to measure the elastic waves propagating along the finger, a 2-axis accelerometer (Analog Devices, ADXL311-JE) was used. As preliminary experiments (not shown in this paper), we measured vibrations of the finger using a phonograph cartridge and confirmed that the bandwidth of the observed vibration was up to 1 kHz. The bandwidth of the accelerometer was selected as 5 kHz to satisfy this condition.

The accelerometer was attached on the backside of the proximal phalanx. Though our goal is to develop a finger ring like device, as pilot experiments, the accelerometer was fixed with adhesive. The axes of the accelerometer are shown in Fig. 2. The data shown in Section 3 and 4 were calculated so that the movement of the accelerometer agrees with the direction of the axes.

2.2. Identification of tapped position

The experiment was designed to confirm that by measuring 2 DOF vibrations, the location of the contact position can be identified. The subjects were asked to tap their palm side of the distal phalanx (Fig.2 Left) or of the middle phalanx (Fig.2 Right) with their thumbs. In this paper, we call tapping on the distal phalanx "DP tapping" and the middle phalanx "MP tapping".

The subjects were 22 – 30 years old. Subject 1, 2, 3, 4 were men and Subject 5 was a woman. The accelerometer was attached on the backside of the proximal phalanx of the index finger. The subjects except for Subject 5 used their left index finger. Subject 5 used her right index finger because Subject 5 had difficulties in tapping with her left index finger. They had no experience to use the device before the experiment. After a brief instruction on how to tap, they were asked to tap their distal phalanxes and middle phalanxes each ten times.

3. Preliminary experiments

Prior to the identification of tapped location, preliminary experiments were conducted to investigate the basic properties of the excited vibration. In this section, the results of the preliminary experiments are briefly described.

3.1. Experimental setup

The purpose of the experiment was to measure the propagating elastic waves on a subject's finger excited by impulsive forces applied on the fingertip. The schematic drawing of the setup is shown in Fig. 3. The

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experimental setups consisted of an impulsive force generation instrument, an accelerometer and fixtures for a finger. The setups, except for the impulsive force generation instrument, were placed on a tabletop vibration isolator in order to avoid the artifact induced by the vibration propagating through the table. The subjects' right index fingers were used for the measurement. The subjects put their hand on a metal table. The subject's finger nails were glued with adhesive to a plastic nail. The plastic nail was attached either on an acrylic bar or string (Fig.4), in order to investigate the effect of the status of fixation on the observed wave. The acrylic bar and the string were

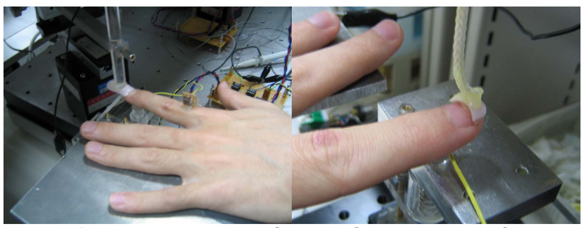

Fig. 4 Two types of the fixation. Left: the subject's finger nail was bonded to an acrylic bar. Right: the subject's finger nail was suspended with a string.

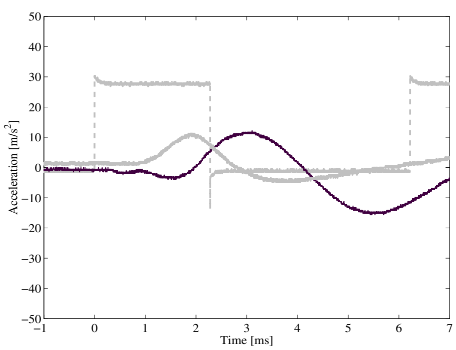

Fig. 5 The observed acceleration excited by impulsive force (fixation: acrylic bar). The black line is the acceleration of z-axis. The gray solid line is the acceleration of x-axis. The gray dotted line is the voltage of the copper wire (the value H means the wire is in contact with the finger).

attached to a Z stage in order to control the position of the finger nail. The vertical position of the finger nail was determined so that the distal, middle and proximal phalanx were all parallel to the horizontal line.

Figure. 3 shows the instrument for applying impulsive forces on the subject's fingertip. The instrument was comprised of a copper wire, an acrylic glass and a spring. The displacement of the spring was the same among the trials. The tip of the copper wire was placed so that it was on the center axis of the subject's index finger. The diameter of the copper wire was 0.8 mm. The copper wire was pulled up to 5 V. The moment the wire was in contact with the surface of the subject's finger, the voltage of the wire fell down to GND.

3.2. Results of the preliminary experiments

Figures. 5 and 6 show the results. The horizontal axis represents time [ms]. The vertical axis represents the acceleration. The black line is the acceleration of z-axis. The gray solid line is the acceleration of x-axis. The gray dotted line is the voltage of the copper wire. When the voltage of the copper wire is "H", it indicates the wire is in contact with the finger. The results in Fig.5 were obtained when the finger was fixed on the acrylic bar. The results in Fig. 6 were obtained when the finger was suspended with a string.

As in Figs. 5 and 6, the waveforms were different when the method of fixation changed. We conducted several other measurements and found that the waveforms were dependent either on the duration of the applied impulsive force or on conditions on the fixation of the finger, rather than the distance between the location of the applied force and the accelerometer.

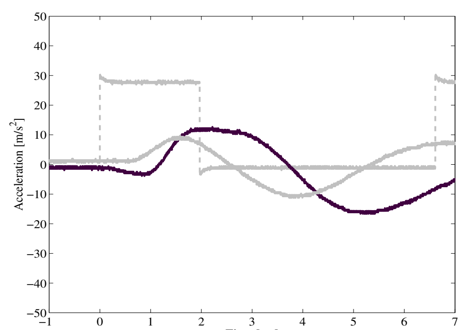

Fig. 6 The observed acceleration excited by impulsive force (fixation: string). The color and type of the lines correspond to the same parameters as in Fig. 5.

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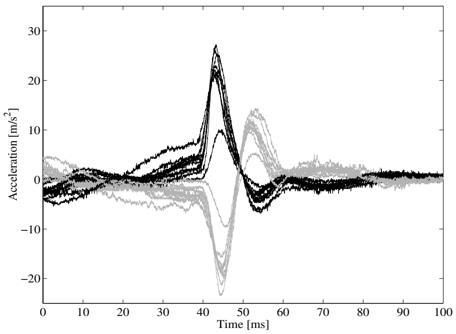

Fig. 7 The observed accelerations for Subject 1 induced by DP tapping. The black line is the acceleration of z-axis. The gray line is the acceleration of x-axis. Ten results are overlaid.

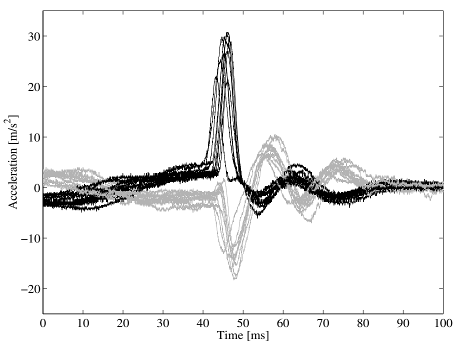

Fig. 8 The observed accelerations for Subject 1 induced by MP tapping. The color and type of the lines correspond to the same parameters as in Fig. 7. Ten results are overlaid.

4. Results

4.1. Observed acceleration

Figures. 7 and 8 show the observed acceleration when the DP and MP of Subject 1 were tapped, respectively. The horizontal axis represents time [ms]. The vertical axis represents the acceleration [m/s^2]. The black and gray lines are the acceleration along the z and x axis, respectively. The accelerometer output of the z axis (the black line) was used as the trigger source. The curves are ten results overlaid.

Two features are seen in Fig. 7 and Fig. 8. First, the amplitude of the acceleration seen before tapping is smaller and the frequency of that is lower compared to the vibrations occurred after tapping. This concludes that the accelerations caused by the swing of the finger and that caused by the tapping are distinguishable. The most useful feature for identifying tapping on DP and on MP is the difference of the phases of the vibrations along z axis and x axis. In Fig. 7, the gray curves are almost like inverted black curves, and the peak of the black curves and gray curves can be observed at the same timing. In contrast, in Fig. 8, the peak of the black curve and that of the gray curves are found at different timings.

Fig. 9 are the results for the remainder of the four subjects. The pictures in the same raw correspond to the same subjects. The pictures in the left and right column are the results for tapping on DP and MP, respectively. The features described above also can be seen in Fig. 9, though the results for Subject 5 seem relatively unstable.

4.2. Analysis method

As discussed in the previous section, the waveforms observed in DP tapping and MP tapping have a significant feature in terms of the phase difference between the vibrations along x-axis and z-axis. The analysis method described in this section utilizes covariance matrices to extract these features and identify DP tapping and MP tapping.

The analyses were carried out in the following process. First, in order to determine the starting point of the vibration, after filtering with digital LPF, the time differences of data were calculated. The starting point was determined so that the time differences of the data first exceed 0.05 at that point. 1024 points of data beginning from 50 points preceding the starting point were cut and used for analyses. The examples of the cut data are shown in Fig. 10.

The i th sampling point of the accelerations of x-axis $x(t_i)$ and z-axis $z(t_i)$ can be plotted on a 2-D plane as a coordinate point ($x(t_i)$, $z(t_i)$). Fig. 11 shows the data in both Fig.10 Left and Fig.10 Right in 2-D plots. The horizontal axis represents the acceleration of x-axis. The vertical axis represents the acceleration of z-axis. The black markers and gray markers correspond to the data in Fig.10 Left and Fig.10 Right, respectively. Each point corresponds to a particular sampling point.

As seen in Fig. 11, the two data set have differences in terms of the variance. To evaluate the difference, we calculated covariance matrices and their eigenvalues. The covariance matrix R was calculated based on the following equations.

$$R\big(x(t), z(t)\big) = \begin{bmatrix} r_{11} & r_{12} \\ r_{21} & r_{22} \end{bmatrix} = \frac{1}{N} X^T X , \qquad (1)$$

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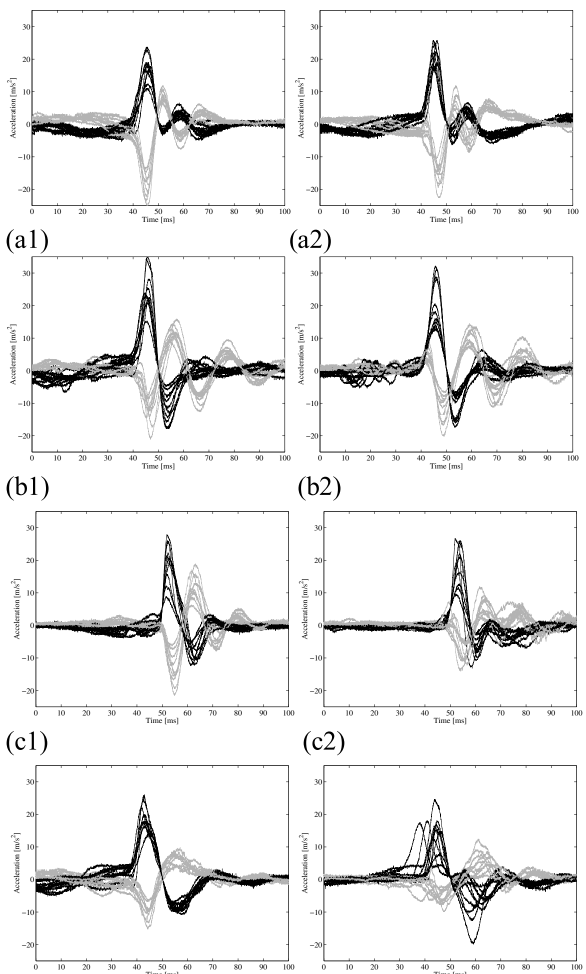
$$X = \begin{bmatrix} x(t_0)-\mu_x & z(t_0)-\mu_z \\ x(t_1)-\mu_x & z(t_1)-\mu_z \\ \vdots & \vdots \\ \vdots & \vdots \\ x(t_N)-\mu_x & z(t_N)-\mu_z \end{bmatrix}, \qquad (2)$$

where N is the number of the data points (in this case N = 1024), μ is the mean value of the corresponding data. The ratio of the eigenvalues of R, $\varepsilon = \lambda_1/\lambda_2$ was used as a parameter to distinguish DP tapping from MP tapping.



(a1) (a2) (b1) (b2) (c1) (c2) (d1) (d2)

Fig. 9 The observed accelerations for Subject 2, 3, 4, and 5. The color and type of the lines correspond to the same parameters as in Fig. 7. The row a, b, c, and d correspond to Subject 2, 3, 4, and 5, respectively. The left and right columns are the data for DP tapping and for MP tapping, respectively.

4.3. Results of the analyses

Fig. 12 shows the results of the analyses for Subject 1. The vertical axis represents the value $\varepsilon = \lambda_1/\lambda_2$. The results of ten trials are aligned in ascending series. Fig. 13 shows the results for the other four subjects.

As seen in Figs. 12 and 13(b), ε for DP tapping and MP tapping are clearly separated. The results for Subject 2 are also divided into two groups with a particular threshold value, with exception of one result. One of the possible explanations on why the results for Subject 4 and 5 are not so successful is that the acquired accelerations were relatively unstable due to subjects' having difficulties in tapping MP with their thumbs.

5. Discussion

As we found in the preliminary experiments, the acceleration waveforms observed at the proximal phalanx were dependent on the conditions on the fixation of the finger. However, in the experiments on the discrimination of DP and MP tapping, even though the subjects could move their finger without any fixations, the observed waveforms were relatively stable. A possible explanation is that tapping motion is almost recognized as a simple 1 DOF motion and, due to the limited range of movement and the posture, the motion is restricted than it is thought to be.

A finger also can be modeled as coupled oscillators comprised of the distal, middle and proximal phalanx connected with dumpers and springs at the joints. The finger vibrations shown in Section 4 are considered to be vibrations caused by three coupled oscillators, rather than elastic waves propagating on the skin or bone. Therefore, if the finger ring device can measure longitudinal or transversal elastic waves in addition to the accelerometer, it is expected that the device can acquire further information on contact condition. Also, the device would be improved by using a 3-axis accelerometer to increase DOF of acquired vibrations.

Compared to the successful cases of Subject 1, 2, and 3, Subject 4 and 5 had difficulties in tapping their middle phalanx. Especially, Subject 5 had difficulties in tapping with her both left and right index finger. In this experiment, all subjects were not trained. The accuracy of the discrimination would increase by training users with appropriate visual or audio feedback.

6. Conclusion

We proposed a tactile interface which utilizes several DOF vibrations excited on the finger. It was shown that with a 2-axis accelerometer placed on the

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backside of the proximal phalanx, tapping on distal phalanx and middle phalanx can be discriminated.

In this study, the number of trials was not sufficient for discussing the accuracy of the device. We are going to carry out larger number of trials with improved devices.

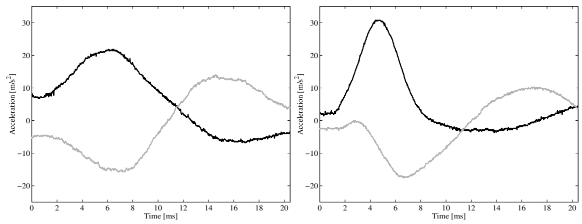

Fig. 10 Examples of the cut data used for the analysis. Left: DP tapping. Right: MP tapping.

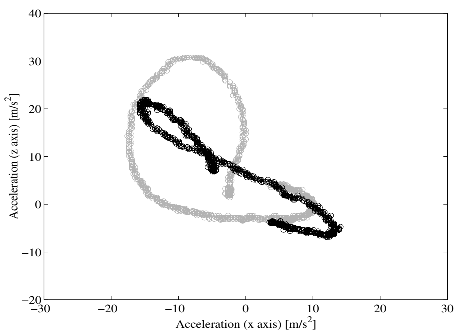

Fig. 11 A 2-D plot of the cut data. The black markers and gray markers correspond to the data in Fig. 10 Left and Right, respectively.

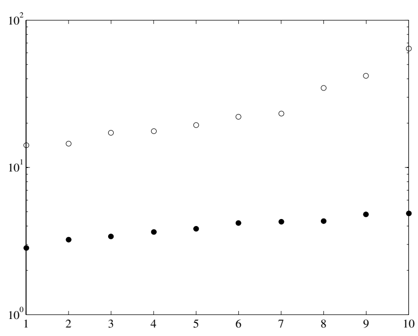

Fig. 12 The results of the analyses for Subject 1. The vertical axis represents the value of ε. The blank and solid marker is the results for DP and MP tapping, respectively. The results are aligned in ascending series.

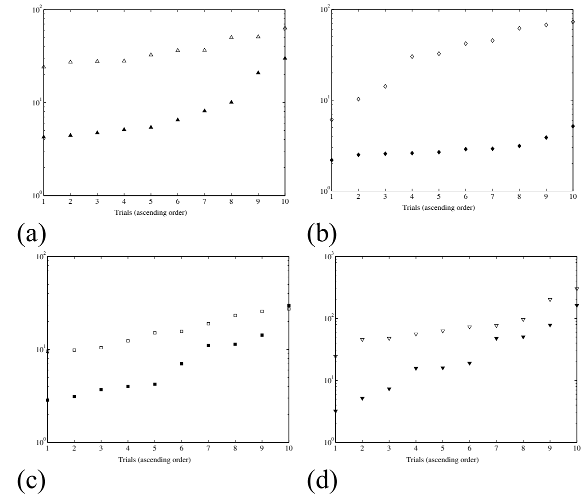

Fig. 13 The results of the analyses for Subject 2, 3, 4, and 5. (a), (b), (c), and (d) correspond to Subject 2, 3, 4, and 5, respectively.

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