Frequency Response Deterioration due to Surface Ridge Abrasion of Tactile Sensors

Muhammad Irwan Yanwari
Dept. Computer Engineering Technology, Polines
Dept. Computer Science, Tokyo Metropolitan University
Tokyo, Japan
yanwari-muhammad@ed.tmu.ac.jp

Shogo Okamoto
Dept. Computer Science, Tokyo Metropolitan University
Tokyo, Japan
okamotos@tmu.ac.jp

***Abstract*—Epidermal ridges are crucial for tactile sensing in both human fingers and synthetic sensors. These ridges are made of compliant materials and susceptible to abrasion damage after iterative use. This study focuses on examining the impact of sensor ridge damage on the acquired signal, which encompasses a broad range of frequency components. We compared the frequency responses of a tactile sensor scanning sandpaper with both intact and damaged sensors. The degradation of signal levels was evident across the 0–1,000 Hz range, with particularly prominent suppression of the peak frequency component. This study demonstrates the frequency-dependent influence of ridge abrasion.**

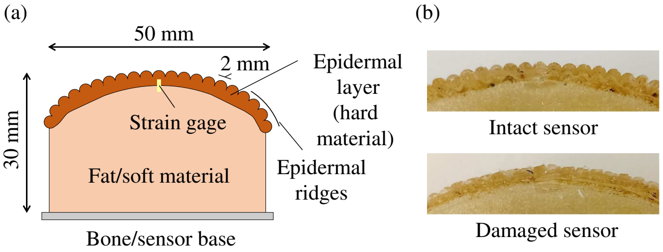
***Index Terms*—Tactile texture sensor, frequency response, abrasion damage, friction**

I. INTRODUCTION

Tactile texture sensors assess the sense of touch in everyday products, such as commercial electronic gadgets and textile products. Epidermal ridges present on such sensors are integral to the tactile sensing mechanism [1]–[3]. These ridges generate vibrations upon interacting with the surface asperity of objects [2], serving as cues for assessing surface textures. Notably, epidermal ridges can amplify tactile signals by a factor of 100, particularly at specific surface wavelengths of objects [3]. The absence of epidermal ridges is anticipated to critically impact the performance of texture sensors. Tactile texture sensors' epidermal ridges, made from compliant material, suffer from abrasion damage after repeated use. However, prior studies have not explored the effects of this damage on their frequency response capabilities. This study focuses on the effect of abrasion damage to the sensor's ridges on the sensor's frequency response across a wide range of frequencies.

II. SENSOR DESIGN

The design of tactile texture sensor followed previous researches [4]–[8]. The sensor architecture primarily comprises two layers designed to mimic the compliance of human skin's epidermal and fat tissues. The inner layer possesses the Young's modulus of 0.17 MPa, while the outer layer exhibits the modulus of 0.82 MPa, aligning closely with estimates derived from anatomical studies of human tissues [9]. Polyvinyl chloride plastisol (Plastic Worm, Two-L Co., Ltd., Japan) was selected as the material due to its tune-able hardness, achieved by adjusting the ratio of softener and hardener mixtures.



Intact sensor
Damaged sensor

Fig. 1. Tactile texture sensor. (a) Sensor design and dimensions. (b) Intact and damaged epidermal ridges.

The dimensions of the sensor were specified as follows: a length of 50 mm, width of 30 mm, and height of 30 mm, with the hard plastic base measuring 60 mm in length, 40 mm in width, and 5 mm in height. The outer region of the sensor was circular, resembling a human finger pad, and featured a semicircular raised pattern on the epidermal layer, simulating the functionality of epidermal ridges. These ridges, approximately four to five times larger than those found on adult human fingers [10], necessitate downsizing in future iterations. In the context of this study, the "intact sensor" denotes a state wherein the ridge structure remains intact, while the "damaged sensor" refers to a condition characterized by worn ridges and flattened top layer, as shown in Fig. 1 (b).

The tactile sensor incorporated a strain gauge (KFGS-1-120-C1-11 L3M2R, Kyowa Electronic Instruments Co. Ltd., Japan) as a transducer to emulate the sensory capabilities of human tactile receptors. The strain gauge, measuring 1 mm in length, possesses the gauge factor of 2.10 and the resistance of 119.6 Ω. Positioned centrally between the inner and outer layers beneath the central ridge, the strain gauge signals are adjusted using a dynamic strain amplifier (DPM-913B, Kyowa Electronic Instruments Co. Ltd., Japan). We set the strain gauge configuration to 1500 $\mu\varepsilon$/V. Data acquisition was facilitated by a data acquisition device (USB-6002, National Instruments Co., USA) controlled by *Data Acquisition Toolbox* of Matlab (2024a, MathWorks Inc., MA).

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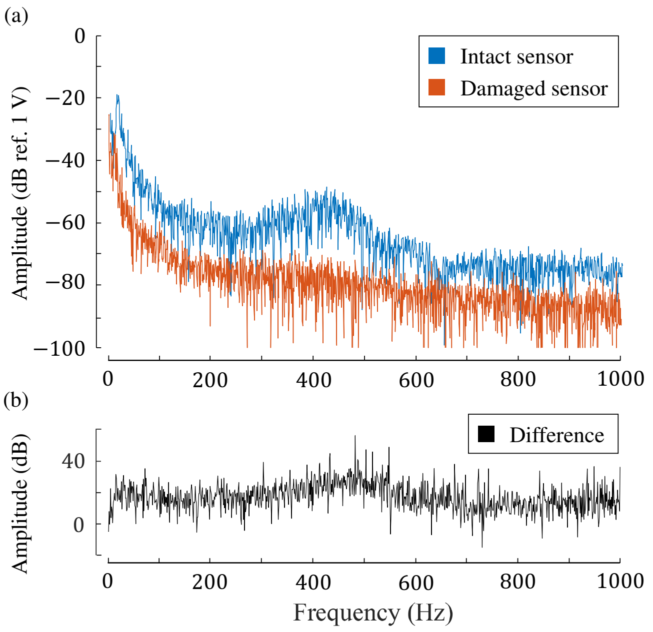

Fig. 2. Amplitude spectrum when the andpaper was explored at 30 mm/s. (a) Intact sensor and damaged sensor. (b) Difference of amplitude spectra between the intact and damaged sensors.

III. PROCEDURES OF MEASUREMENT

The specimen used in this experiment was a sandpaper (Sankyo Rikagaku Co. Ltd., Japan) with a 400-grit level. The specimen width and length were 4 cm and 13 cm, respectively. Sandpaper offers a relatively uniform dot-density within each specific grit size.

The sensor was mounted onto a six-degree-of-freedom articulated robotic arm (MyCobot, Elephant Robotics Co. Ltd., China). It traversed a 13 cm specimen at a velocity of 30 mm/s, while the normal contact force remained constant at $\sim$1 N. This scanning operation was repeated 1,330 times.

IV. RESULTS

Fig. 2 (a) shows the amplitude spectra of the strain gauge signal across 0–1,000 Hz for the intact and damaged sensors. The spectrum for the intact sensor is a mean value from the 7th, 14th, 21th, 28th, and 35th scans, while the damaged sensor data are from the 1,302th, 1,309th, 1,316th, 1,323th, and 1,330th scans. For the entire frequency range, the signal levels for the damages sensor were smaller than those for the intact sensor. Fig. 2 (b) shows the difference between the two spectra, indicating that the reduction in signal intensity varied across frequencies. Especially, the difference was prominent at approximately 400–600 Hz.

In the intact sensor configuration, a distinct peak emerged within the frequency range of 300 Hz to 500 Hz. After the sensor ridges were damaged, this peak became attenuated and was no longer visible.

V. DISCUSSIONS

After the iterative use, the epidermal ridges of the tactile texture sensor were abraded. We observed a degradation of signal amplitude resulting from this abrasion-induced damage. This decrease in signal intensity was not uniform across all frequencies, with certain frequencies exhibiting a more pronounced decline compared to others. Specifically, the decreases in the 400–600 Hz range were most prominent, as shown in Fig. 2 (b). For other frequency ranges, the signal level deterioration was approximately 20 dB. The weakening of signals across this broad range indicates a decrease in the sensor's sensitivity to subtle differences in textures. From this finding, we suggest the necessity of a frequency formation method depending on the sensor's abrasion level.

Another solution to abrasion damage is to incorporate a repairing function into the sensor using healable materials [7]. This approach would prevent degradation from reaching critical levels. By periodically healing the sensor at specific intervals (e.g., every 100 scans), the signal degradation caused by abrasion can be kept below 20 dB until the sensor is replaced.

As shown in Fig. 2 (a), the peak at approximately 400 Hz of the intact sensor diminished after the epidermal ridges were worn off. Hence, this prominence may originate from the natural frequency of the ridges. This frequency depends on the dimensions of the sensor and ridges. It is noted that the ridges of the sensor used in this study were four to five times larger than those of human fingers, and the results cannot be directly compared with actual fingers. The vibration test of the human finger pad typically exhibits peak frequencies smaller than 400 Hz [11], [12].

VI. CONCLUSIONS

The focus of this investigation was on assessing the impact of sensor ridge damage on the received signal across a wide range of frequencies. Tactile texture sensors are susceptible to abrasion-induced damage after repeated use, which consequently alters the signal levels. Our experimental findings indicate that the degradation of signal levels depends on the frequency. The abrasion does not uniformly decrease the signal levels across the entire frequency band; hence, this study suggests the necessity of countermeasures to rectify the sensory signals according to the degree of abrasion damage. As a prospective extension of this research, it is imperative to devise strategies aimed at preserving the amplitude pattern of the acquired signal during repetitive usage scenarios. Healing function of the sensor ridges can be one of the promising approach to deal with the problems of the abrasion damage of the sensor ridges [7].

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