Proceedings of the 2003 IEEE/RSJ
Intl. Conference on Intelligent Robots and Systems
Las Vegas, Nevada · October 2003

Tactile Sensor with Automatic Gain Control

Makoto KANEKO and Ryuta HORIE

Faculty of Engineering
Hiroshima University
1-4-1 Kagamiyama, Higashi-Hiroshima, Hiroshima 739-8527, JAPAN

Abstract

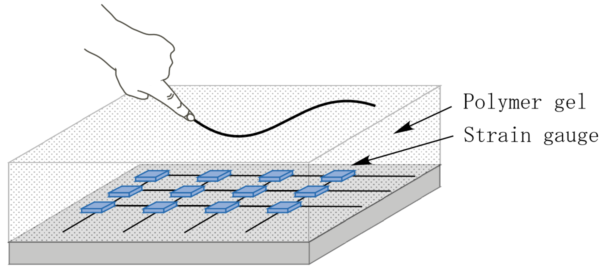
This paper proposes a new tactile sensor capable of automatically adjusting the sensitivity of each sensor unit, depending upon the contact information. Suppose a strain gauge based tactile sensor composed of multiple sub-sensor units and a single AD-DA port. For such a sensor system, we introduce two key components; the Analyzer, how to determine the contact force quickly from each sub-sensor unit, and the Automatic Gain Controller (AGC), how to automatically change the gain for each unit, according to the sensory information. For example, the sensor can automatically cope with both the signal saturation due to an unexpectedly large input and the resolution control depending upon the contact force. The basic idea of the sensor system is verified by experiments.

Key words: *Tactile Sensor, Automatic Gain Controller*

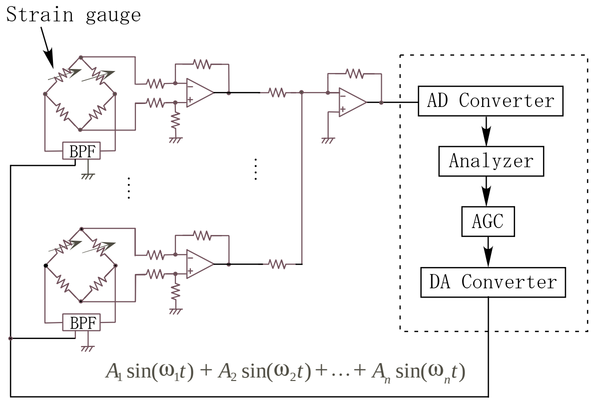
1 Introduction

Human touch sensing can cover a wide range of contact force. For example, it can easily discriminate from just a naive touch to a large impulsive force. Four different kinds of sensors register deformation of the skin caused by contact with external objects. Meissner and Merkel endings lie close to the skin surface and have high spatial resolution. In the fingerprint skin of the hand Meissner endings are located between the papillary ridges of the dermis, while the Merkel endings are located at the ends of these rides. Pacinian corpuscles and Ruffini endings are embedded deep in the skin and hence their receptive fields are broader. These sensing organs contribute to not only recognizing different sensation of touch but also greatly expanding the range of contact force. As a result, human can keep a wide dynamic range of contact force depending upon how much force is applied.

On the other hand, the gain tuning is a big issue for an artificial tactile sensor. For example, it easily results in saturation for an excessive large contact force, and the resolution is drastically down for an extremely small contact force. Another request is perhaps to increase the sensing resolution near the area where the contact happens. Under these background, the goal of this work is to propose a new tactile sensor with a self-gain tuner, where the sensor can automatically change the gain according to the input force applied. Especially, we focus on a strain gauge based tactile sensor system as shown in Fig.1, where it is composed of multiple sub-sensor units, Analyzer and Automatic Gain Controller (AGC). We would note that since increasing the number of sub-sensor units can be easily achieved by putting the same set additionally, the system in Fig.1 holds a basic form of this type of tactile sensor. From now on, we simply consider the hardware having a single input and output port and n sub-sensor units, where each unit has an appropriate band-pass-filter so that it can incorporate a sinusoidal input with the predetermined frequency alone into the bridge circuit. For such a sensor system, the computer sends an input signal including n different kinds of



(a) Tactile array sensor



(b) An example of sensor circuit

Fig. 1: Overview of the proposed sensor system

base functions with predetermined frequency for all sub-sensor units, through a single DA port. After passing each band-pass-filter, the input signal for each bridge circuit results in a sinusoidal signal with the predetermined frequency alone. The amplitude of the output signal from each bridge circuit is proportional to the force applied to the sub-sensor unit. All output signals are summed up and fed into the computer through an AD converter. For such a system, there are two key issues; the Analyzer, how to determine the force quickly from each sub-sensor unit, and the AGC, how to automatically achieve the gain control for each sub-sensor unit. Instead of applying the Fast Furier Transformation (FFT), the Analyzer can easily and quickly compute the contact force for each sub-sensor unit by simply multiplying the sinusoidal function with the same frequency and by applying an appropriate low pass filter. Then, the AGC changes the amplitude for each base function for the input signal. By introducing a simple feedback loop into the AGC, the feedback system always tries to keep the output from each sub-sensor unit to a reference value, irrespective of the contact force applied in each element. This control scheme ensures to avoid the saturation for any sub-sensor unit, and it can increase the loop gain automatically for a sub-senor unit being in an extremely small contact force at the same time. For example, when an excessively large contact force is applied to a particular sub-sensor unit, the amplitude of the base function is drastically reduced so that the output signal may converge to the reference value. Also, when a small contact force is given to a sensor unit, the amplitude of the base function increases so that it may converge to the reference value. The policy of AGC is often utilized for adjusting a lightening condition automatically for a CCD camera through lens. Another utilization is for controlling the voice level in microphone for either avoiding the saturation or pulling up the gain for a weak input level. Though the AGC is well known for both areas, as far as we know, this is the first work on tactile sensor with AGC.

After briefly reviewing related works, we introduce the basic working principle of the proposed sensor system in section II where both the Analyzer and the AGC are precisely described. In section III, we design and develop a strain gauge based tactile sensor and show a couple of experimental results to verify the basic idea. Finally, we add some discussions before concluding remarks.

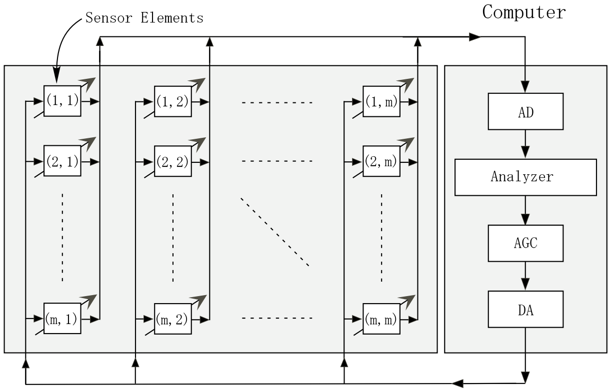


Fig. 2: Signal flow of the proposed sensor

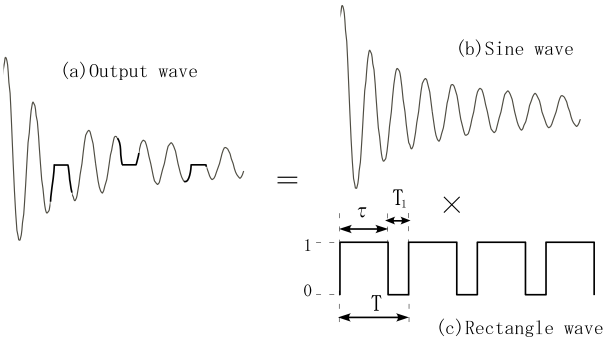


Fig. 3: The output signal from computer

2 Related Works

Interest in the area of robot tactile sensing goes back to the early 1960s with the work of H. Ernst[1]. So far, a number of tactile sensors have been designed and developed in various viewpoints, for example, sensitivity, resolution, linearity, elasticity, minimal wiring, easiness of fabrication and so forth. Tactile sensors [2]−[5] are often designed as $M \times N$ arrays of $M + N$ wires where each sensing element is read individually by multiplexing the wires. A common problem for this type of sensor is the large number of wires needed for reading data from the sensory array. There are various works discussing approaches for reducing the amount of wiring [6]−[8], where the sensor is mostly implemented as a filter. Recently, a novel wireless tactile sensing has been proposed by Shinoda and Oasa [9] where they have completely removed any wire by utilizing a coil for receiving and transmitting an electrical power through a wireless coupling. They also introduced an elasticity into the sensor by putting many resonators into elastic skin, so that the sensor may be deformable for a contact with an environment.

This work particularly focuses on the Automatic Gain Control for a strain gauge based tactile sensor with a single input-output wire. While a number of tactile sensors [9]-[13] have been proposed up to now, as far as we know, this is the first work on tactile sensor with AGC.

3 Working Principle

3.1 Outline

Fig.2 shows the signal flow of the proposed sensor where it is composed of sub-sensor units, Analyzer and AGC. The computer sends an input signal including n different kinds of base functions with predetermined frequencies for all sub-sensor units, through a single DA port. The function

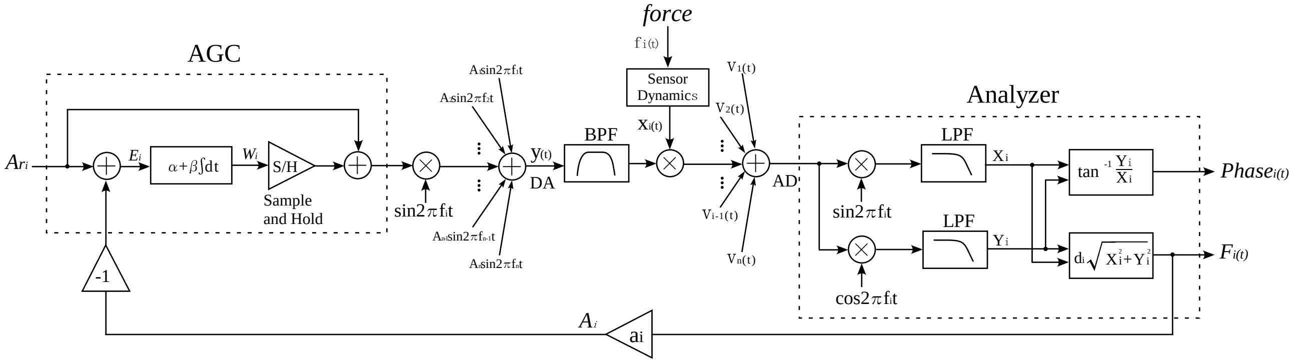


Fig. 4: The feedback loop for the i-th sensor unit

has the following form with respect to time t:

$$\begin{aligned} y(t) &= A_1\sin(2\pi f_1 t) + A_2\sin(2\pi f_2 t) + \cdots \\ &\quad + A_i \sin(2\pi f_i t) \end{aligned} \tag{1}$$

where A_i and f_i denote the amplitude of the i-th base function and predetermined frequency for each sub-sensor unit, respectively. After passing each band-pass-filter(BPF), the input signal for each bridge circuit results in a sinusoidal signal with the predetermined frequency alone. For example, the i-th sub-sensor unit picks up $A_i\sin(2\pi f_i t)$ alone. As a result, the amplitude of the output signal $V_i(t)$ from the i-th bridge circuit is proportional to the force applied to the sub-sensor unit and given by,

$$V_i(t) = G_i \times \frac{\Delta R_i}{2R} A_i \sin(2\pi f_i t + \phi_i) \tag{2}$$

where G_i, ϕ_i, ΔR_i, and R are the gain of the amplifier, phase difference between the supply voltage and $V_i(t)$, the change of resistance due to the contact force, and the resistance of strain gauge for the i-th sub-sensor unit, respectively. All output signals are summed up and fed into the computer through an AD converter by utilizing an appropriate amplifier, as shown in Fig.1. As a result, the input signal to the computer is given by,

$$V_{sum}(t) = \sum_{i=1}^{n} V_i(t),\ |V_{sum}(t)| < V_{input|max} \tag{3}$$

where $V_{input|max}$ denotes the maximum voltage that the AD converter can accept. The force applied to each sub-sensor unit is evaluated by the Analyzer and the AGC adjusts the amplitude of each base function to satisfy the following requirements; the avoidance of signal saturation where the $|V_{sum}|$ should not exceed the $V_{input|max}$, and the high gain control for the sensor unit where the contact force is small. More precise discussions on both the Analyzer and the AGC will be given in the latter sections.

3.2 Analyzer

As shown in eq.(1), the summation of outputs from the sub-sensor units is given by the form of summation of sinusoidal functions whose frequencies coincide with the base functions. We would note that the contact force is proportional to the amplitude of the output from each sub-sensor unit. Let us now consider how to pick up the amplitude from the input signal to the computer. There are a couple of ways to do it. While the most popular one is to use the Fast Fourier Transformation (FFT), it takes time for analyzing all frequency components and therefore, may not be suitable for utilizing it in a real time feedback loop. Since the frequency for each sub-sensor unit is given in advance, it is not necessary to analyze the power spectrum corresponding to all frequency components continuously but enough for examining only for the frequencies matching with individual base functions. In order to obtain the amplitude, let us now multiply the total output signal with a sinusoidal function having the frequency of base function as follows:

$$V_x(t) = V_{sum}(t) \times sin(2\pi f_i t) \tag{4}$$

$$V_y(t) = V_{sum}(t) \times sin(2\pi f_i t + \frac{\pi}{2}) \tag{5}$$

All components except the one with f_i disappear with a combination of low pass filter(LPF) and the only component concerning with f_i can remain without disappearing. Let $X_i(t)$ and $Y_i(t)$ be the output signal after taking an appropriate LPF for the signal with the correlation operation, respectively. Finally, we can compute the force component $F_i(t)$ and the phase shift $Phase_i(t)$ by the following equations:

$$F_i(t) = d_i\sqrt{X_i^2(t) + Y_i^2(t)} \tag{6}$$

$$Phase_i(t) = \arctan\frac{Y_i(t)}{X_i(t)} \tag{7}$$

where d_i is a constant and determined by a calibration test. $Phase_i(t)$ provides us with the direction of contact force, such as either pushing or pulling. Since a sub-sensor unit normally receives a pushing force only, it is not necessary to compute $Phase_i(t)$ for practical use. We would note that this computation is quick enough for achieving a real time operation, since the computation is focused on the limited frequency only.

3.3 Automatic Gain Control (AGC)

The main role of AGC is to automatically avoid the signal saturation for AD and to change the resolution depending upon the contact information. We implement the following tuning law for adaptively changing the amplitude $A_i(t)$.

$$\begin{aligned} E_i(t) &= A_{r_i}(t) - A_i(t) \qquad (8) \\ W_i(t) &= \alpha E_i(t) + \beta \int_0^T E_i(t)dt \qquad (9) \end{aligned}$$

where $A_{r_i}(t)$, $A_i(t)$ and $W_i(t)$ are the the i-th reference value of A_i, the amplitude from the i-th sub-sensor unit and the modified value for the i-th amplitude, respectively, and α and β are appropriate constants, respectively. For example, by keeping $A_{ri}(t)$ constant A_{ro} with respect to time, we can avoid the signal saturation automatically under $nA_{ro}/a_i < V_{input|max}$. Under such a tuning, we can automatically increase the gain for the sensor unit where the contact force is small at the same time, where a_i is a constant for converting the dimension from force to voltage.

There is a remark for changing $W_i(t)$ with respect to time. The change of $W_i(t)$ is done by rewriting the memory data for a DA converter into a new one. For example, let T_1 and T be the rewriting time for a DA converter and the time period for resetting new data for the memory, respectively, as shown in Fig.3, where the actual signal given by Fig.3(a) can be regarded as the multiplication between the continuous function as shown in Fig.3(b) and the rectangular signal as shown in Fig.3(c). Therefore, an actual output signal from a DA converter can be expressed by the following Fourier expansion,

$$\begin{aligned} V_i(t) &= A_i(t)\sin(2\pi f_i t) \times \sum_{n=-\infty}^{\infty} \frac{\tau \sin(n\pi \frac{\tau}{T})}{n\pi} e^{jn\omega t} \\ &= A_i(t)\sin(2\pi f_i t) \times \{\frac{\tau}{T} + 2\sum_{n=1}^{\infty} \frac{\sin(\frac{n\pi\tau}{T})}{n\pi}\cos(n\omega t)\} \\ &= \frac{\tau A_i(t)}{T}\sin(2\pi f_i t) + 2A_i(t)\frac{\sin(\frac{\pi\tau}{T})}{\pi}\sin(2\pi f_i t)\cos(\omega t) \\ &\quad + 2A_i(t)(\frac{\sin(\frac{2\pi\tau}{T})}{2\pi})\sin(2\pi f_i t)\cos(2\omega t) + \cdots \qquad (10) \end{aligned}$$

where $\tau = T - T_1$. From Eq.(10), we can say that when making the feedback loop active with high frequency, $y_a(t)$ includes new sinusoidal signals whose frequencies are given by $|f_i + n/T|$ and $|f_i - n/T|$ where the lower script "a" denotes an actual value. Since those new signals surely influence on the amplitudes not only for f_i but also for other frequency components, we have to keep τ/T as unity as possible so that $\sin(n\pi\tau/t) \to 0$. This can be achieved by setting a large T, which means that making the feedback loop active should be slow enough compared with the memory rewriting time. This is the reason why we implement the sample hold in the feedback system, as shown in Fig.4.

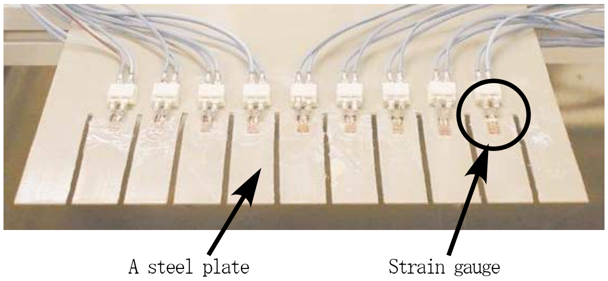


Fig. 5: Overview of tactile sensor

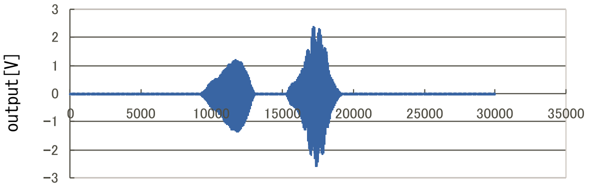
4 Experiments

4.1 Experimental System

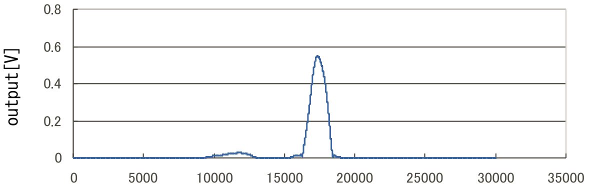
Fig.5 shows an overview of the experimental system where a steel plate is partially cut so that we can make sub-sensor units. Two strain gauges are pasted in both sides of each sub-sensor unit and this configuration allows us to achieve a temperature compensation for each sensor unit. The DA converter capable of producing an analogue signal with the rate of 30kHz sends the compound signal including all base functions. The voltage signal for the bridge circuit is obtained through a BPF for the signal given by the DA converter. The BPF plays an important role for picking up the inherent signal for the sub-sensor unit from the signal from DA converter. In order to keep a high decoupling capability among sub-sensor units, we utilize the Biquad type BPF whose quality factor is 150. This quality factor guarantees the attenuation with more than 100dB between two neighboring base functions. We believe that such a capability of BPF is sharp enough for blocking all other frequencies without the limited one and for applying the inherent input voltage to each individual bridge. The output from each unit is summed up after an instrumentation amplifier whose amplification ratio is approximately 1000. As a result, the input line to the AD converter with the sampling rate of 5kHz includes the signal with amplitude-modified multi-frequencies. In order to keep $\tau/T \approx 1.0$, we set T=250ms and τ=200ms, which results in τ/T=0.80.

4.2 Experimental Results

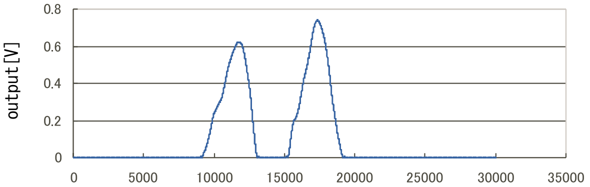
Fig.6 shows an experimental results for two sub-sensor units whose inherent frequencies are 300Hz and 600Hz in



(a) Mixture sine wave



(b) 313Hz amplitude



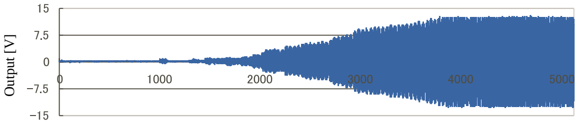
(c) 604Hz amplitude

Fig. 6: Experimental results without AGC

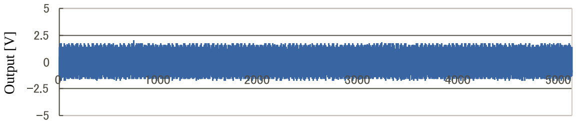
design, respectively. Due to a small shift of frequency, however, their actual frequencies are 313Hz and 604Hz, respectively. We first touch the sub-sensor unit with 600Hz and then touch both units simultaneously. Fig.6 (a), (b), and (c) show the input signal to the computer, two output signals from the Analyzer, respectively. From Fig.6, we can see a contact signal during t=0.9-1.3 sec for the unit with 604Hz and two contact signals during t=1.5-1.9 sec for both units, respectively. There is a small output during 0.9-1.2 sec for the unit with 313Hz, while no input is given during the time interval. This is perhaps due to the insufficient blocking capability of the BPF of the unit with 313Hz.

Fig.7 shows that the tactile sensor easily results in saturation under the constant amplitude without AGC, where (a) and (b) are time histories of sensor output and DA output, respectively. Fig.7(a) shows the signal saturation of AD converter after t=3900ms.

Fig.8 shows the experimental results for examining the effect of the AGC under that the contact force is changed from small to large one; where (a), (b), (c) and (d) are time histories of sensor output during t=0-500ms, DA output during t=0-500ms, sensor output during t=0-5000ms, and DA output during t=0-5000ms, respectively, and T_d is the recommended time interval for acquiring data. We would note that the output from the sensor unit includes the delay coming from the BPF as well as LPF. Since the force data during such a delay period do not reflect the input force appropriately, we have to start the actual sampling after such a delay period. From Fig.8(c) and (d), we can see that the gain decreases as the contact force increases.

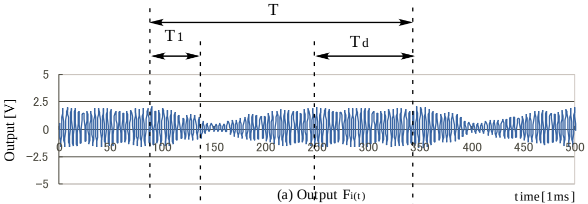


(a) Output Fi(t)

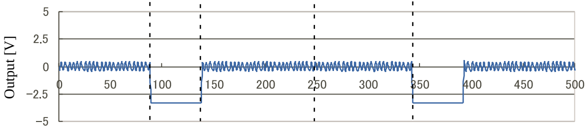


(b) Input to the sensor unit

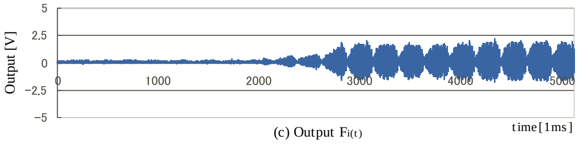
Fig. 7: Experimental results without AGC



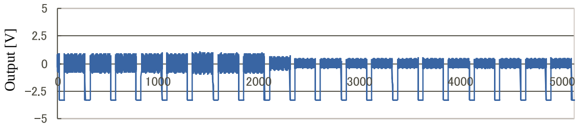
(a) Output Fi(t)



(b) Input to the sensor unit



(c) Output Fi(t)



(d) Input to the sensor unit

Fig. 8: An experimental result with AGC

5 Discussions

So far, we assume that a tactile motion is slow enough to ensure that any dynamic effect can be neglected during the sensing motion. Now, suppose that the tactile motion is sufficiently fast to ensure that we have to consider the dynamic effect. Since each sub-senor unit can be modeled by a mass-spring system, it will vibrate for such an impulsive or a dynamic input. Under such inputs, the sensor will start to vibrate and the oscillation of the i-th sensor unit $X_i(t)$ with respect to time is given by,

$$X_i(t) = B_i e^{-pt} \cos(2\pi f_{si} t) \qquad (11)$$

where B_i, f_{si} and p denote the amplitude, the natural frequency for the i-th sub-sensor unit, and damping factor, respectively. For such a vibration, the sensor output signal can be expressed by

$$V_i(t) = G_i B_i e^{-st} \cos(2\pi f_{si} t) \times A_i \sin(2\pi f_i t + \phi_i) \qquad (12)$$

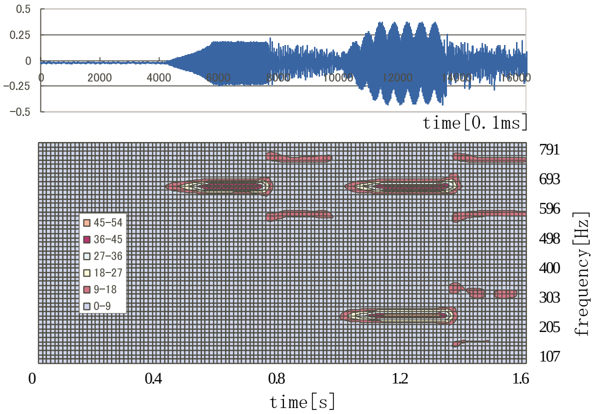


Fig. 9: Experimental result with dynamic effect

Eq.(10) can be easily rewritten by the following form.

$$V_i(t) = function(f_i - f_{si}, f_i + f_{si}) \tag{13}$$

This means that the sensor output includes the frequency components with both $f_i - f_{si}$ and $f_i + f_{si}$, if the dynamics of the sensor becomes dominant. In such a case, we have to avoid any collision of frequency among f_i, $f_i - f_{si}$ and $f_i + f_{si}$, so that we can decompose all frequency components successfully. If $f_i \gg f_{si}$ is guaranteed, we can avoid frequency interference. Fig.9 shows an experimental result where the first impulsive input is given for the sensor with 604Hz at t=0.45[sec] and the second input is given for both sensors with 604Hz and with 313Hz at t=1.1[sec], respectively. Fig.9(a) and (b) show the time histories of the sensor output and the short time Fourier Transformation, respectively. We would note that after the main contact signal, we can clearly observe the vibration power coming from the sinusoidal signals whose frequencies are $f_i - f_{si}$ and $f_i + f_{si}$, respectively. The power for the frequencies with both $f_i - f_{si}$ and $f_i + f_{si}$ can be utilized to judge whether the sensor is in vibration or not.

6 Concluding Remarks

We proposed a new tactile sensor system composed of strain gauge based sub-sensor units, the Analyzer, the Automatic Gain Controller (AGC), and a single AD and DA port. The main results of this work can be summarized as follows:

1. By combining a compound signal including various frequencies and appropriate band-pass filters (BPF), we showed that we can control the input signal for each sensor unit adaptively, simply with the change of the amplitude for each sinusoidal signal with the inherent frequency for the sensor unit.
2. Instead of utilizing a Fast Fourier Transformation (FFT), we picked up the amplitude in each frequency component by multiplying the sinusoidal function with the same frequency as the given one. We showed that the approach is appropriate for a real time operation.
3. We showed that the AGC with PI gains is effective not only for avoiding the signal saturation but also for changing the resolution depending upon how much the contact force is.

This work is partially supported by the Ministry of Education and Science in Japan with the grant number of 14350132.

References

[1] H. A. Ernst: MH-1-A Computer-Operated Mechanical Hand, *Proc. of the AFIPS Spring Joint Computer Conference*, vol. 21, pp39-51, 1962

[2] R. D. Howe and M. R. Cutkosky: Touch Sensing for Robotic Manipulation and Recognition, *in The Robotics Review 2, Cambridge*, MA: MIT Press, pp55-112, 1992

[3] H. R. Nicholls and M. H. Lee: A Survey of Robot Tactile Sensing Technology, *Int. J. of Robotics Res.*, vol. 8, no.3, pp3-30, 1989

[4] R. S. Fearing: Tactile Sensing Mechanism, *Int. J. of Robotics Res*,vol.9, no.3, pp3-23, 1990

[5] M. Shimojo, M. Ishikawa, and K. Kanaya: A Flexible High Resolution Tactile Imager with Video Signal Output, *IEEE ICRA*, pp348-391, 1991

[6] I. J. Busch-Vishniac: Spatially Distributed Transducers. Part II, Augmented Transmission Line Models *Trans ASME*, vol.112, pp381-390, 1990

[7] Y. Yamada, K. Shin, N. Tsuchida, and M. Komai: A Tactile Sensor System for Universal joint Sections of Manipulator, *IEEE Trans. of Robotics and Automation*,vol.9, pp512-517, 1993

[8] M. Nilsson: Tactile Sensors and Other Distributed Sensors with Minimal Wiring Complexity *IEEE/ASME Trans. on Mechatronics*, vol.5, no.3, pp253-257, 2000

[9] H. Shinoda and H. Oasa: Wireless Tactile Sensing Element Using Stress-Sensitive Resonator *IEEE/ASME Trans. on Mechatronics*, vol.5, no.3, pp258-265, 2000

[10] M. Shimojo, M. Shinohara, and Y. Fukui: Human Shape Recognition Performance for 3-D Tactile Display, *IEEE Trans. on Systems, Man, and Cybernetics*, Part A, vol. 29, No. 6, pp.637-644, November 1999

[11] J. S. Son and R. D. Howe: Tactile Sensing and Stiffness Control with Multifingered Hands, *Proc. of the 1996 IEEE Int. Conf. Robotics and Automation*, vol. 4, pp.3228–3233, 1996

[12] H. Maekawa, K. Tanie, K. Komoriya, and M. Kaneko: Development of a Finger-Shaped Tactile Sensor and its Evaluation by Active Touch, *Proc. of the 1992 IEEE Int. Conf. Robotics and Automation*, vol. 2, pp.1327–1334, 1992

[13] M. Ueda, et al.: Tactile Sensors for Industrial Robot to Detect Slip, *Proc. of the 2nd ISIR*, IIT Research Institute, Chicago, pp.63–76, 1972