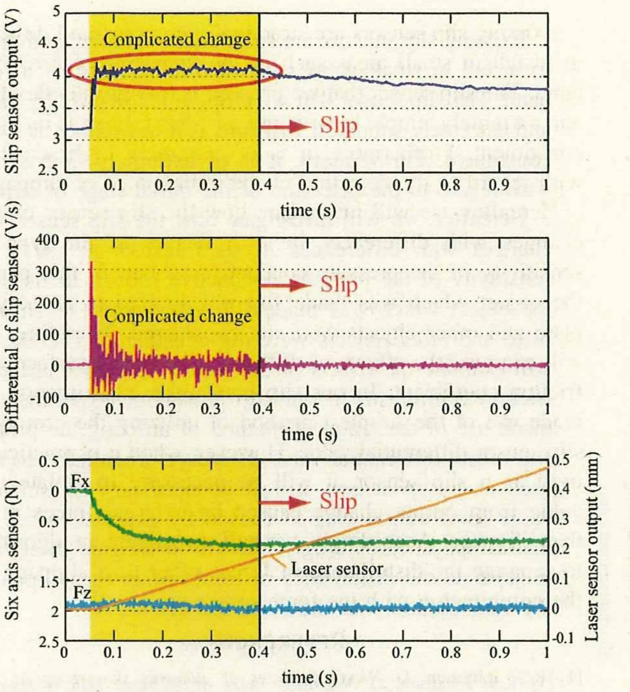

Fig. 9. Output change between 0 (s) and 1 (s)

IV. Slip prevention by Prototype of slip sensor

From the results shown in the prior chapter, detection of initial stage slippage appeared possible by focusing on the output change of the prototype slip sensor produced in the initial stage of slippage. In this experiment, the object slip was detected utilizing the differential value of prototype slip sensor output, and this information was fed back to the auto-linear stage, and the slippage of the object was prevented.

A. Experimental setup

The experimental apparatus utilized in these experiments is shown in Fig.10. The prototype of slip sensor was deployed on the horizontal plane. Above the sensor was placed an acrylic plate of 3 *mm* in thickness, which was sandwiched between the load cell above and sensor below. The load cell was attached to the automatic Z stage, and by the movement of the stage, it was possible to apply any grip force to the acrylic plate. The acrylic plate was connected by wire through a pulley to a cup-like container. To create slippage, a transverse load could be applied to the acrylic plate by putting weights into this container.

That is, an algorithm was used to monitor the sensor output differential value just before the occurrence of slip displacement and move the stage a fixed amount if the value exceeded the threshold, thus increasing the grip force. The threshold of $\pm 5\ V/s$ was established in this experiment by comparing the change in sensor differential values when slippage was produced with when no slippage occurred. The sampling cycle of the slip sensor was 1 *ms*, and the control cycle of the automatic stage was 10 *ms*. After a small grip force (approximately 1.5 *N* in this experiment) was applied to the acrylic plate, weights of 50 *g*, 100 *g*, and 150 *g* were placed into the container, and measurements were made of prototype slip sensor output, grip force change, and displacement of the acrylic plate from the time the container was gently released.

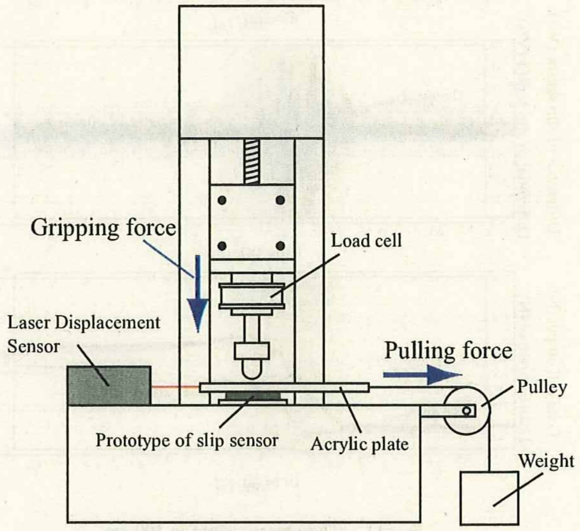

Fig. 10. Experimental equipment for slip prevention experiment

B. Experimental result and Discussion

The results of 100 (*g*) are shown in Fig.11. The upper graph indicates the prototype slip sensor output, the middle graph shows the sensor output differential value, and the lower graph displays the load cell output, and the laser displacement sensor output (resolution: 0.1 μm). From this data, we found that when the slip sensor differential value exceeded an established threshold, the grip force (load cell value) was restored. In each case, no slippage visible to the naked eye was produced. That is, it was possible to prevent slippage for three different types of transverse loads applied. Table I summarizes the convergent load cell value (grip force) and the displacement quantity of the acrylic plate as measured by the laser displacement sensor. It is apparent that the quantity of the displacement increased with each increase in the transverse load, and the grip force utilized also increased. Adjustment of the grip force was realized in response to the weight of the load.

In this experiment, there was not the sharp change in slip displacement immediately prior to the onset of slippage as was the result obtained in the prior chapter (Fig.8-upper graph). This is attributable to the fact that the transverse load was applied slowly and produced a slow shear deformation of the rubber. However, if the transverse load were to be applied suddenly, there would be a sharp change as seen in the preceding section. The sudden addition of a transverse load is the cause of greater slippage, and in such a case, action that prevents slippage is possible through utilization of the change.

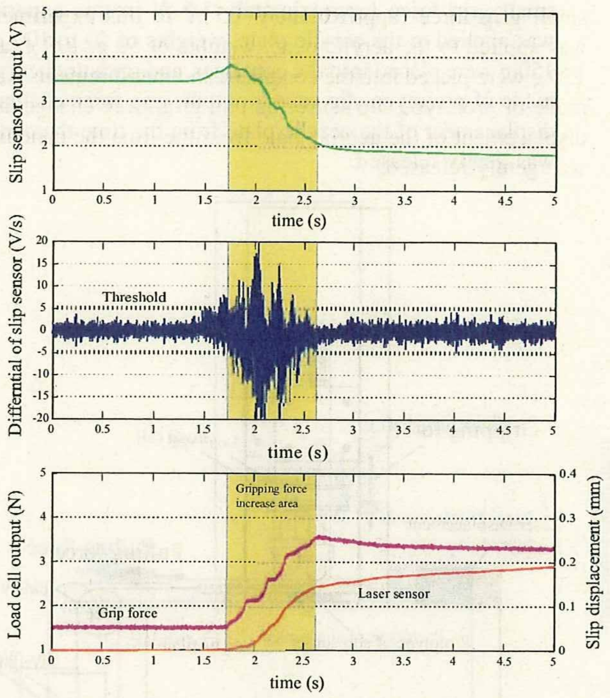

Fig. 11. The object weight is 100 (*g*)

TABLE I

GRASPING FORCE AND DISPLACEMENT FOR OBJECT WEIGHT

	Weight		
	50(g)	100(g)	150(g)
Displacement (mm)	0.12	0.18	0.25
Grasping force (N)	2.6	3.3	4.2

V. SUMMARY AND FUTURE WORKS

We manufactured a prototype of a slip sensor utilizing the special characteristics of pressure conductive rubber and performed experiments in which an object was made slip over the sensor. We were able to find the following results:

- It was found that slip sensor output rose just before onset of slippage, and complecated output change was produced. Detection of the initial stage of slippage (slip prediction) was possible due to these factors.
- There was a small change in slip sensor output over the interval where slippage was produced. This was attributable to the detection of stick-slip produced between the sensor and the object.

We also performed experiments in which the initial stage of slippage was detected utilizing the change in prototype slip sensor output, and a simple algorithm was used to prevent object slippage. As a result, we were able to prevent slippage for the three quantities of transverse load applied. Moreover, the convergent grip force value varied with the size of the transverse load, and the feasibility of grip force adjustment in response to a transverse load was shown.

Existing slip sensors are structurally complex and difficult to install in small areas such as the fingertips of a robotic hand. The slip sensor that we propose is low-profile, flexible, and extremely simple in structure as it has rubber as its main constituent. Furthermore, it is of extremely high sensitive with regard to the detection of the initial stage of slippage.

Hereafter, we will investigate how the slip sensor output changes with differences in such factors as the type or sensitivity of the pressure conductive rubber. In this paper, the object which was made slip was limited to an acrylic plate and other objects were not considered. Therefore, we will examine the effects of differences in object surface and friction coefficient. In our slip prevention experiments, we made use of the simplest method of utilizing the prototype slip sensor differential value. However, when it is practically used as a slip sensor, it will be necessary to isolate this value from output change caused by external forces other than slippage. Accordingly, we will investigate an algorithm to separate the disturbance of forces other than slippage by the combination with the force sensor etc.

REFERENCES

[1] R.S. Johanson, G. Westling, *Roles of glabrous skin receptors and sensorimotor memory in automatic control of precision grip when lifting rougher or more slippery objects*, Exp Brain Res, Vol.56, pp. 550-564, 1984

[2] R.S. Johanson, G. Westling, *Signals in tactile afferents from the fingers eliciting adaptive motor responses during precision grip*, Exp Brain Res, Vol.66, pp. 141-154, 1987

[3] M.R. Trembly, M.R. Cutkosky *Estimating Friction using Incipient Slip Sensing During a Manipuration Task* , Proc. IEEE Int. Conf. on Robotics and Automation, pp.429-434, 1993

[4] J.S. Son, E.A. Monteverde and R.D. Howe, *A Tactile Sensor for Localizing Transient Events in Manipulation*, Proc. IEEE Int. Conf. on Robotics and Automation, pp.471-476, 1994

[5] T. Maeno, K. Kobayashi, N. Yamazaki*Relationship between Structure of Finger Tissue and Location of Tactile Receptors*, JSME Trans, Series C, Vol.63, No.607, pp.881-888, 1997(in Japanese)

[6] Y. Koda, T. Maeno, *Grasping Force Control in Master-Slave System with Partial Slip sensor*, Proc. IEEE/RSJ Int. Con. on Intelligent Robots and Systems, pp.4641-4646, 2004

[7] T. Maeno, S. Hiromitu, T. Kawai, *Control of Grasping Force by Detecting Stick/slip Distribution at the Curved Surface of an Elastic Finger*, Proc. IEEE Int. conf. on Robotics and Automation, pp.3895-3900, 2000

[8] H. Shinoda, S. Sasaki, K. Nakamura, *Instantaneous Evaluation of Friction based on ARTC Tactile Sensor*, Proc. IEEE Int. Conf. on Robotics and Automation, Vol.3, pp.2173-2178, 2000

[9] A. Ikeda, Y. Kurita, J. Ueda, Y. Matsumoto, T. Ogasawara, *Grip force control for an elastic finger using vision-based incipient slip feedback*, IEEE/RSJ Int. Conf. on Intelligent Robots and Systems, pp.810-815, 2004

[10] N. Saito, T. Satoh, H. Okano, *Grasping Force Control in consideration of Translation and Rotational Slippage by a Flexible Sensor*, IEEE Annual Conf. on Industrial Electronics, pp.3892-3897, 2006

[11] A. Ito, N. Tujiuchi, T. Koizumi, H. Oshima, Y. Nojiri, Y. Tsuchiya, N. Hirama, S. Kurogi, *Development and Structure Evaluation of Small Sensor Element for Distributed-Type Tri-Axial Force Sensor of Robot Finger*, IEEE Int. Conf. on Robotics and Biomimetics, pp.1309-1314, 2007

[12] D. Accoto, F. Damiani, R. Sahai, *A thermal slip sensor for biorobotic applications*, IEEE Int. Conf. on Robotics and Automation, pp.1523-1528, 2007

[13] Shang Zhen-dong, Wang Qunyan, Han Jianhai, Xianhong Xu, *Sliding Sensor and Soft Grasping of Electron Hydraulic Servo Manipulator*, IEEE Int. Conf. on Mechatronics and Automation, pp.1459-1464, 2006

[14] S. Teshigawara, M. Ishikawa, M. Shimojo, *Development of High Speed and High Sensitivity Slip Sensor*, Proc. IEEE Int. conf. on Intelligent Robots and Systems, pp.47-52, 2008

High Sensitivity Slip Sensor Using Pressure Conductive Rubber

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***Abstract*—Slip detecting tactile sensors are essential to achieve a human-like gripping motion with a robot hand. In previous researches, we have proposed flexible, thin and lightweight slip sensor utilizing characteristics of pressure conductive rubber. However, It was hard for this sensor to distinguish between the object slip and the normal force change. Therefore, we consider the separative method using high frequency elements generated by object slipping. In this paper, we design the information processing method and developed the sensor detecting both contact and initial slip in high sensitivity and a simple composition.**

I. INTRODUCTION

Humanoid robots are researched to assist and support human life at the various research institutions. However, in order to advance the robot to the human living space, there is a need to adapt to its environment. If a humanoid robot thinks about the operation of grasping an object, the robot hand must have many degrees of freedom, and using it, they must be able to grasp a variety of objects and operate them. To do this operation, tactile sensors are required to obtain information such as contact position and contact force, and slip. Especially if robot want to grasp in the minimum force without destroying the object and to operation the object dexterously, the sensation of slip plays an important role[1].

So far, a variety of sensors have been developed such as type of sensors to detect vibration when the slip occurred[2][3], and type of sensors to detect the occurrence of stress and strain change[4][5]. Many types of sensors detect changes which occur just before the slip of an object, or "initial slip". However, these sensors are complex structures and there is a problem of wiring, saving smaller and lighter. Also, as you need to embed inside the sensitive element, we consume time and the cost.

In our laboratory, we propose a thin ($0.5mm$) and flexible slip sensor using pressure sensitive conductive rubber[6]. This sensor uses a peculiar resistance change when shear deformation of the pressure conductive rubber occurs [7]. However, It is difficult to separate a resistance change of the normal force and a resistance change of the object slip. In other words, it is hard to realize the separation with the normal direction force change and the object slip. Therefore, we designed the use of a complicated resistance change immediately before a slip occurs (It is a round part in fig.1).

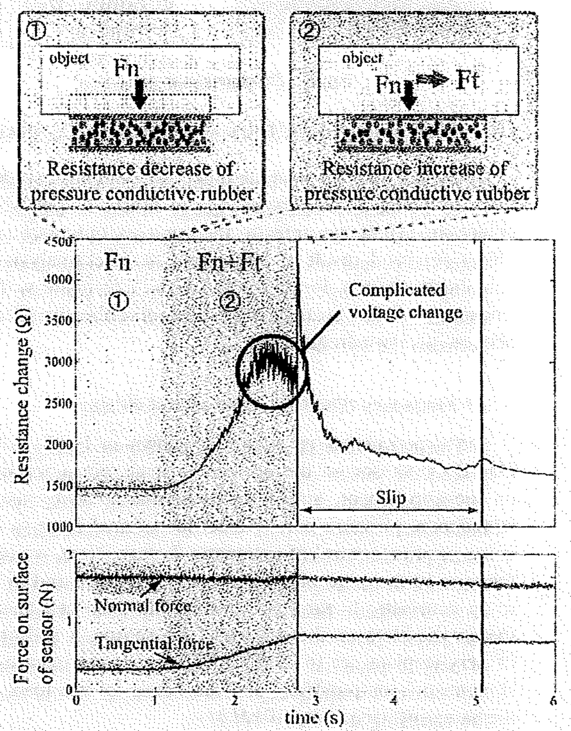

Fig. 1. Resistance change of pressure conductive rubber when object slipped

II. STRUCTURE OF SLIP SENSOR

The configuration of this sensor is shown in Fig. 2. In the configuration of the slip sensor, two electrodes are alternately coiled around a spiral structure, and on the electrodes rests pressure conductive rubber ($6mm \times 6mm$). The electrode is connected to a DC power supply ($5V$) through a resistance of $1k\Omega$. Sensor output is a voltage potential between the electrodes(V_{out}). Since this sensor utilizes rubber, it is flexible, light weight, and low-profile (0.5 mm). We estimate that the minimum size of this sensor is $3mm\times$ $3mm\times$ $0.5mm$. Moreover, As an amplifier circuit is not needed, it is an extremely simple structure. Also, the larger the detector plane, saving wiring (just only 2 wires).

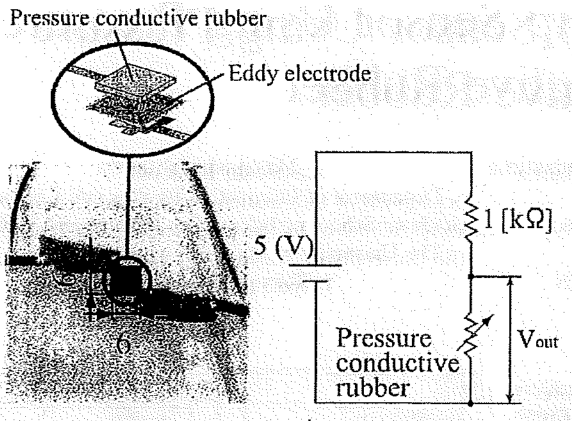

Fig. 2. Structure of slip sensor

III. Slip sensor's output and frequency analysis

We expect that can separate object slip and normal direction force by using a complex change in sensor output when the object slip. Here, we refer to the complex output change for object slip, and result of continuous wavelet analysis to the complicate change. Furthermore, we will compare with a the frequency of the normal force, and describe the difference between the two frequencies.

A. Frequency components when object slip

The experimental apparatus is shown in Fig.3. After we placed the sensor on the horizontal plane, put a acrylic plate on the slip sensor, and add the normal force by using the hemisphere pressure part. We set the normal force to $2N$ by using position control of automatic Z-stage. Next, we installed the wire in the edge of the placed acrylic plate and hitched it to an automatic linear stage through the load cell and slided the acrylic plate on the surface of the sensor. A sliding speed of acrylic plate set to $1mm/s$. Moreover, we measured the slip sensor's output(V_{out}) and the output of the load cell by the sampling frequency $10kHz$.

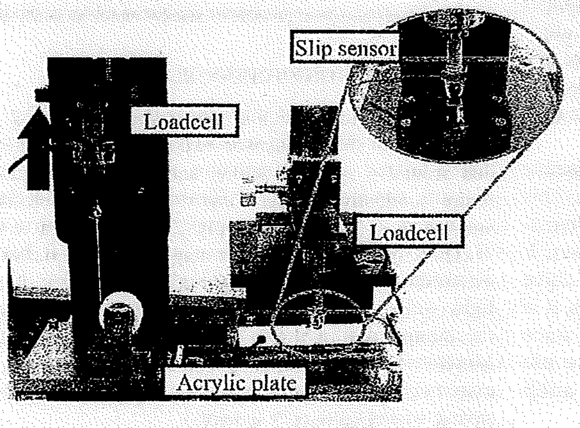

Fig. 3. Experimental apparatus : object slip generator

Experimental data is show in Fig.4. The vertical axis shows the output of the load cell and slip sensor's output and the horizontal axis is time. Seeing a change of tensile force, it increase till $3s$ and it is constant after the time of vertical line. This fact means the change from static friction to kinetic friction. Therefore, the slip between the surface of slip sensor and an acrylic plate are occur from the time of vertical line. On the other hand, looking at the slip sensor's output, it is found that a complex voltage has occurred immediately before an acrylic plate slides.

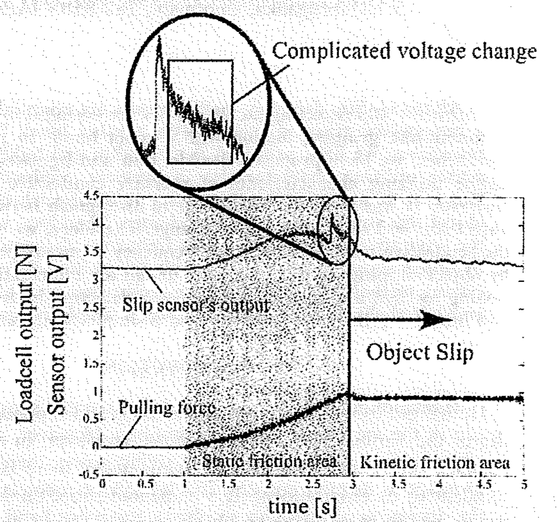

Fig. 4. Experimental results : Output of slip sensor and Tensile force of object

Next, we show the result of a continuous wavelet transform in Fig.5. The upper graph is a change of slip sensor's output, middle graph is a continuous wavelet transform for the upper graph. This vertical axis is "scale" corresponds to the frequency and the horizontal axis is time. Upper side of vertical axis shows low frequency, and lower side is a high frequency. Also, the shade of color shows the power of frequency. Moreover, the bottom three graphs are enlarged graghs of square areas. In the first stage of the voltage change by the tensile force addition, the high frequency component has hardly included and power is also small. On the other hand, we found that the high frequency component increases aiming at immediately before the plate's beginning to slip, and the high frequency of $1kHz$ or more appears. After that, this sensor can detect initial slip by using this high frequency components.

B. Compare with frequency components of normal direction force change

Here, we compare the frequency component by object slip with the frequency component by normal direction force change, and we perform the continuous wavelet transform for output change of normal direction force addition. The experimental equipment is shown in Fig.6. As shown, we

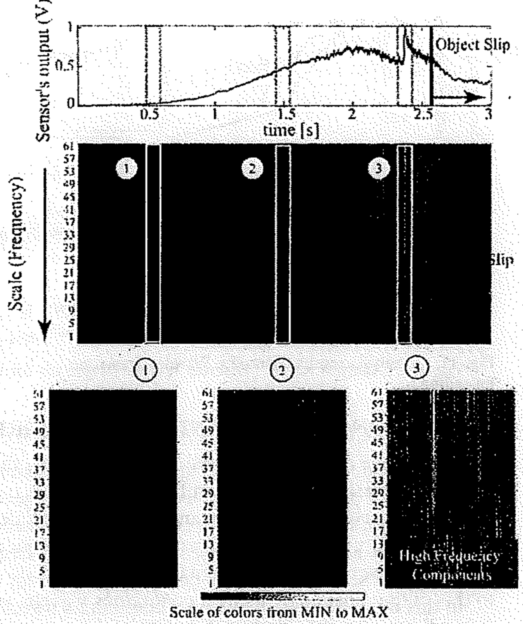

Fig. 5. Continuous Wavelet Transform for the object slip

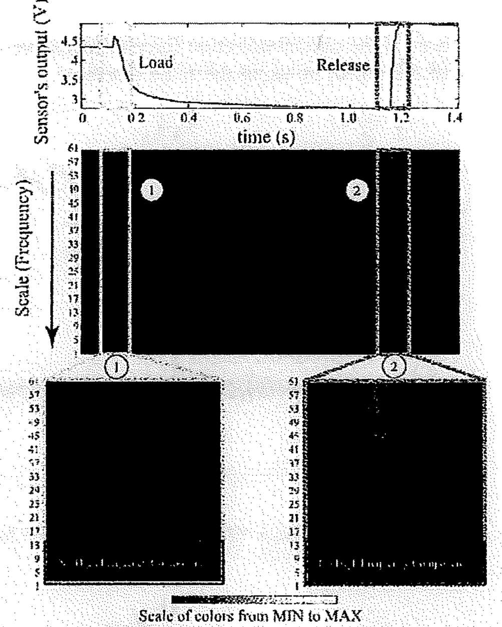

Fig. 7. Continuous Wavelet Transform for the loading and unloading

placed the sensor on a horizontal plane and put $20mm \times 20mm$ acrylic plates on this sensor. Next, we add a perpendicular load to normal direction of the surface of slip sensor using a automatic linear stage. We measured for the output change of the slip sensor at this time and perform continuous wavelet transform to this data.

The result of this experiment is shown in Fig.7. From the result, we found that frequency for normal direction force change is about $600Hz$ at highest. The high frequency component did't appeared when the object slips. From above, it was clarified that the frequency component generated by slip was higher than that by the normal direction force change. Therefore, we can separate these change by using the difference of this frequency components.

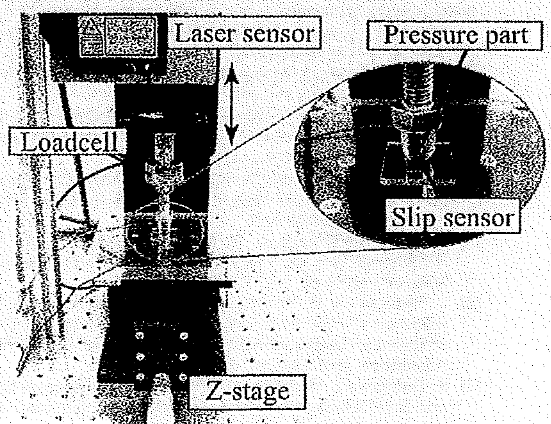

Fig. 6. Experimental Equipment : Adding normal force

IV. Separation Method using High Frequency Component

From above, we found that the high frequency component of $1kHz$ or more is included in a complex voltage change when object slip is generated. In addition, it is higher than the frequency when only normal force is added. That is, it seems that it is possible to separate slip and the normal force change by the detection of this high frequency component. Then, we propose the technical way : usage the Discrete Wavelet Transform (As follows : DWT). When perform DWT, the outputs giving the detail coefficients (from the high-pass filter) and approximation coefficients (from the low-pass). This time, we measured the output change of slip sensor under following conditions, and excused DWT of level1 to these data by using the wavelet of Haar.

- Set initial normal force to $2N$, $3N$, $4N$ and slided an acrylic plate (on Fig.3)
- Add normal force on the surface of slip sensor (on Fig.6)

This corresponds to processing that puts the high-pass filter for the output of the slip sensor. Analytical results are shown in Fig.8, 9, 10, and Fig.11. These upper graph is slip sensor's output, and lower graph is DWT for this. As a Fig.11, when normal force change only occur, the wavelet coefficient has hardly changed. On the other hand, from Fig.8 and Fig. 10, it can be observed the wavelet coefficient increase just before object slip occur. Therefore, we can separate the initial slip of the object and the normal force change by setting the threshold to the result of filtering by DWT. Also, there is hardly a difference in the power of the wavelet coefficient when the normal direction power changes as $2N$, $3N$, and $4N$. Hence, even if the normal direction force changes, we can detect slip of the object by using the same threshold.

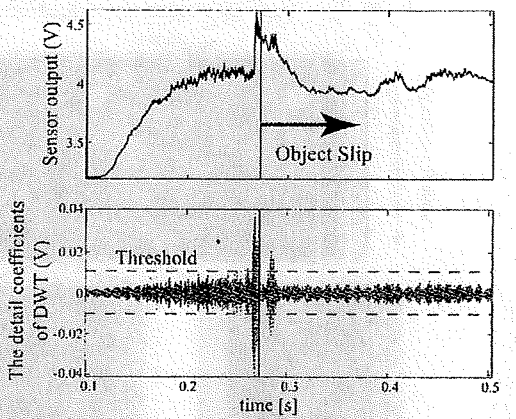

Fig. 8. Analysis results : Discrete Wavelet Transform for the object slip. Initial normal force is $2N$

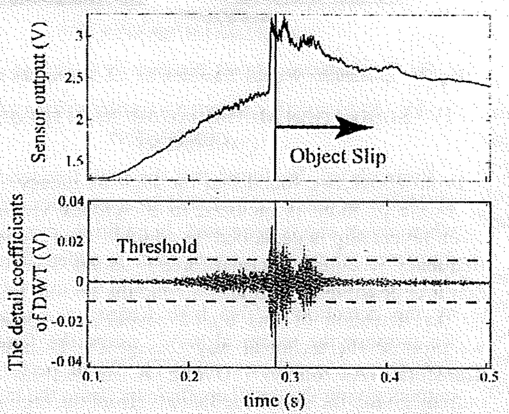

Fig. 9. Analysis results : Discrete Wavelet Transform for the object slip. Initial normal force is $3N$

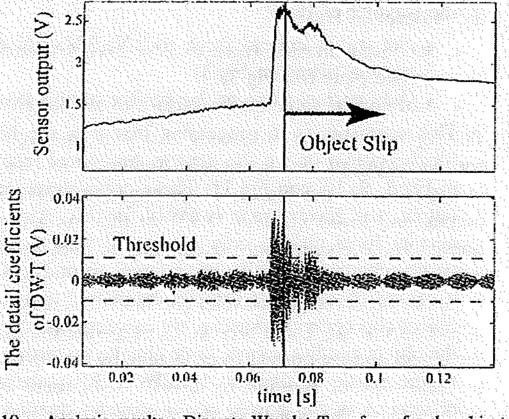

Fig. 10. Analysis results : Discrete Wavelet Transform for the object slip. Initial normal force is $4N$

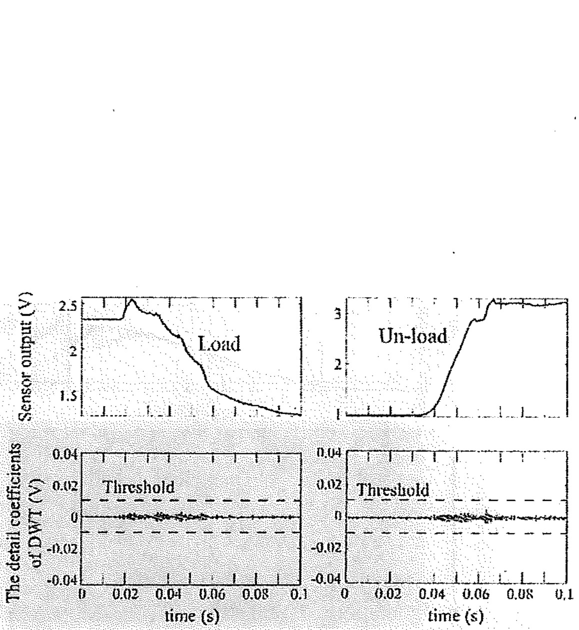

Fig. 11. Analysis results : Discrete Wavelet Transform for the loading and unloading

V. CONCLUSIONS AND FUTURE WORKS

We produce a simple structural slip sensor using the characteristics of pressure conductive rubber. If the object is slided on this sensor, a complex output change occur immediately before the object slip. And, we discovered the high frequency component of several kHz to be contained as a result of analyzing to this output change by using a continuous wavelet transform. In addition, we found that this high frequency component is about one digit higher than the frequency component in the normal direction force change. Then, we proposed the algorithm which separate information of slip from the slip sensor's output change concluded the normal direction force change by using the difference of this frequency component. Here, we extracted the frequency component of slip by using the function of the high-pass filter of DWT. As a result, we found that can separate slip and normal force change by setting the threshold to the detail wavelet coefficient of DWT(level1).

In the future, we verify when the object collides with the surface of the sensor, and will confirm the performance of this slip detection method. In addition, we will research the influence changing the slip velocity and the slip object.

REFERENCES

[1] R.S. Johanson, G. Westling, *Roles of glabrous skin receptors and sensorimotor memory in automatic control of precision grip when lifting rougher or more slippery objects*, Exp Brain Res, Vol.56, pp. 550-564, 1984

[2] J.S. Son, E.A. Monteverde and R.D. Howe, *A Tactile Sensor for Localizing Transient Events in Manipulation*, Proc. IEEE Int. Conf. on Robotics and Automation, pp.471-476, 1994

[3] M.R. Trembly, M.R. Cutkosky *Estimating Friction using Incipient Slip Sensing During a Manipuration Task*, Proc. IEEE Int. Conf. on Robotics and Automation, pp.429-434, 1993

[4] H. SHINODA, K. MATSUMOTO and S. ANDO, *Acoustic Resonant Tensor Cell for Tactile Sensing*, Proc. IEEE Int. Conf. on Robotics and Automation, pp.3087-3092, 1997

[5] K. Noda, I. Shimoyama, *A Shear Stress Sensing for Robot Hands -Orthogonal arrayed Piezoresistive Cantilevers standing in Elastic Material-*, pp.63-66, HAPTICS' 06

[6] S. Teshigawara, K. Tadakuma, A. Ming, M. Ishikawa, M. Shimojo *Development of High-Sensitivity Slip Sensor Using Special Characteristics of Pressure Conductive Rubber*, Proc. IEEE Int. conf. on Robotics and Automation, pp.3289-3294, 2009

[7] S. Teshigawara, M. Ishikawa, M. Shimojo, *Development of High Speed and High Sensitivity Slip Sensor*, Proc. IEEE Int. conf. on Intelligent Robots and Systems, pp.47-52, 2008