Paper

Multi-functional Sensing Approach for Material Discriminating and Property Analyzing

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The aim of this study is to propose a multi-functional tactile sensor with a simple structure to imitate the human hand. It is characterized by the small sensing area and the moving measurement method. A step-by-step method is used to realize the multi-functional sensing and in each step, different material characteristics are sensed. By analyzing the output of the sensor, three material properties, i.e., metal or non-metal, hard or soft, and curved or plane surface, and the environment temperature can be obtained. A detailed analysis of the step-by-step method to the sensor is made.

Keywords: Multi-functional sensor, Material discriminating, Property analyzing

1. Introduction

With the research and development of the robot sensor, the technical requirement for tactile sensors in industry becomes vast. The ability of recognizing some features of measured material is required. In recent years, various intelligent tactile sensors with abilities of the human hand have been investigated by many research groups. [1]~[3] We designed a novel multi-functional sensor, which achieves the multi-functional sensing objective by a single sensor and it is characterized by a small sensing area together with a moving measurement method. By moving measurement is meant the method of measuring the whole material by moving the sensor instead of staying at one point. The sensor was installed on the robot hand in order to fulfill the moving measurement objective.

As a common sense, different sensors are used when there are different variables to be sensed simultaneously. Different from the popular technique, known as the compound sensing, multi-functional sensors have been developed in the last decade. In a very straight way, a multi-functional sensor can be defined as a sensor having more than one sensing function, i.e., a sensor capable of sensing in more than one different way. That is, the quantities being measured affect more than one single sensor's input or compact structure of the sensing component is forcibly requested. There may be various types of multi-functional sensors such as physical, biological, chemical etc. depending on their sensing functions. In this paper, the physical multi-functional sensor will be discussed. Results have shown that the multi-functional sensing increased the sensing objects discriminative property of the sensor.

Multi-functional sensing technique consists in two aspects. One is to establish proper function, i.e., measurement equations depending on the mathematical model drawn from the physical structure of the sensor. The other is to setup appropriate algorithms of data reconstruction on the outputs of sensor multi-functions.

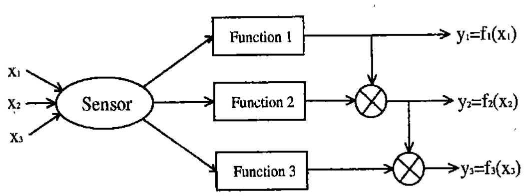

Fig. 1. Sensor with three functions.

The schematic structure of our proposed multi-functional sensor is shown in Fig.1 where x_1, x_2 and x_3 are three quantities under test, with the sensor outputs y_1, y_2 and y_3 being their estimations. Three steps are required to complete the whole measurement. Firstly, y_1 is tested according to function 1. Secondly, y_2 is tested according to y_1 and function 2. Finally, y_3 is tested according to y_2 and function 3. Different signal values are representative of the process status. Thus in a process, we may measure x_1, x_2 and x_3 at different steps. All such measured values together represent the process status. In our study, function 1,2 and 3 are temperature measurement, material discrimination and property analysis respectively. From the outputs y_1, y_2 and y_3, many material properties analyses are available such as metal or non-metal, hard or soft and plane or curved surface.

2. Structure and Principle of the Sensor

The structure of the proposed sensor is illustrated in Fig.2. A plastic pipe with a diameter of 3 mm is used as the inner tube of this sensor and at the bottom of the pipe, fine copper wire is wound to make a coil with 100 turns. There is an iron core in the middle of the sensor. One end of the iron core is fixed on the housing and the

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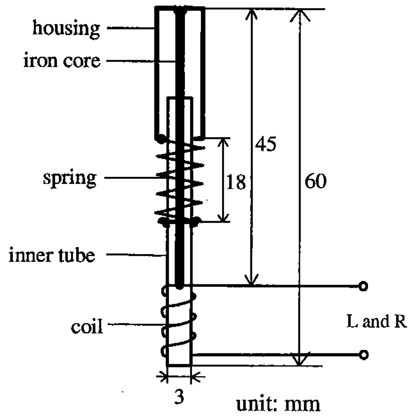


Fig. 2. Structure of the sensor.

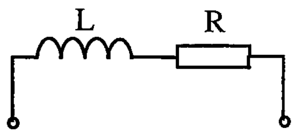


Fig. 3. Equivalent circuit.

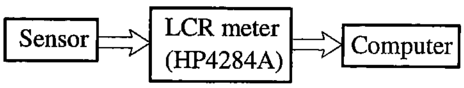


Fig. 4. Experimental setup.

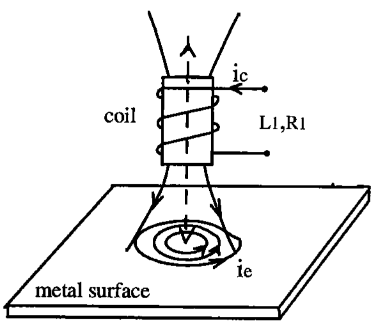


Fig. 5. Eddy effect.

other stays just on the top of the coil where can be defined as the null position. The inner tube can move back or forth along the iron core. The spring is mounted to connect the housing and the inner tube together. Consider the equivalent circuit of the sensor shown in Fig.3. This circuit can be regarded as a series circuit composed of an inductance L and a resistance R where R is the effective resistance of the coil. When experiments were carried out, the inductance and resistance values (outputs of the sensor) are measured by an LCR meter (HP4282A), from which the signal is interfaced with the computer for data processing. From the point of view of the sensor structure, the following sensing functions can be realized:

2.1 **Material Variety Discriminating** When an AC current flows in a coil in close proximity to a conducting surface, the magnetic field of the coil will induce circulating (eddy) currents in that surface. The

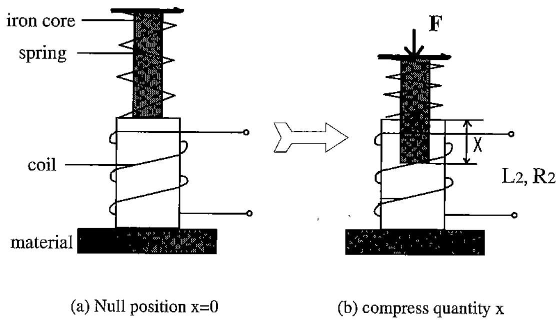


Fig. 6. Material property analyzing.

magnitude and phase of the eddy currents will affect the loading on the coil and thus its impedance. A number of factors will affect the eddy current response. The main factors are the material conductivity ρ and permeability μ. The conductivity of a material has a so direct effect on the eddy current flow that conductivity can be measured by this technique. But for ferrous metals, the permeability has a very significant influence on the eddy current response. In the present study, this technique is used for metal and non-metal materials or ferrous and non-ferrous metals discriminations. That is,

$$\begin{cases} L_1 = L_1(\rho, \mu) \\ R_1 = R_1(\rho, \mu) \end{cases} \quad \cdots\cdots\cdots\cdots \quad (1)$$

2.2 **Material Property Analyzing** In this measuring function, the sensor is used to analyze if the material to be measured is hard or soft and has a curved or plane surface by means of force measuring. Normally, the iron core stays at the null position, as shown in Fig.6 (a). Should some force be exerted onto both ends of the sensor, a vertical displacement of the inner tube will emerge causing the spring compressed. This will make the iron core insert into the coil that results in the variation of the inductance and the resistance of the coil, as shown in Fig.6 (b). Once the force is cancelled, the spring will return to its normal length and then the iron core will go back to the null position. Thus, the output indicates the exerted force, i.e.

$$\begin{cases} L_2 = L_2'(F) \\ R_2 = R_2'(F) \end{cases} \quad \cdots\cdots\cdots\cdots \quad (2)$$

where F is the exerted force. According to Hooke's Law

$$F = kx \quad \cdots\cdots\cdots\cdots \quad (3)$$

F is proportional to x, where x is the compress quantity of the spring and k is the elastic coefficient of the spring. Since the elastic coefficient of the spring we used is 490 N/m, when the force is exerted from 0 N to 4.9 N, the compress quantity varies from 0 mm to 10 mm. After that, substituting Eq. (3) in Eq. (2), we obtain

$$\begin{cases} L_2 = L_2'(F) = L_2'(kx) = L_2(x) \\ R_2 = R_2'(F) = R_2'(kx) = R_2(x) \end{cases} \quad \cdots\cdots\cdots \quad (4)$$

If the bottom of the sensor just touches the material surface vertically and when a fixed force is exerted to the top of the sensor, the spring inside the sensor will be compressed and some compress quantity will occur. The spring can transmit the same force to the material surface. If the material is hard, it means there is no deformation on the material surface, we will obtain inductance and resistance values, which correspond to the force value. If the material is soft, some deformation will occur on the surface, the spring's compress quantity will be smaller than the above case and different inductance and resistance will be obtained. Using this technique, hard or soft surface of the material can be analyzed. Furthermore, if the material is hard but has a curved surface, when a force is exerted to the top of the sensor and the sensor is moved horizontally, afterwards, values at different points will be obtained. By contracting these measured values and the force character figure of the sensor, the spring's compress quantity at each point will be known, and then, curved or plane surface of the material can be detected.

Fig.7 shows the force characteristics of this sensor. Experiment was carried out in order to find out the inductance and resistance characteristics with the exerted force. A block of acrylic was put under the bottom of the sensor because there is no eddy effect comparing with the metal materials. From Fig.7, we can see that the more force, the greater the inductance and the resistance. This is because iron is a ferrous material, its

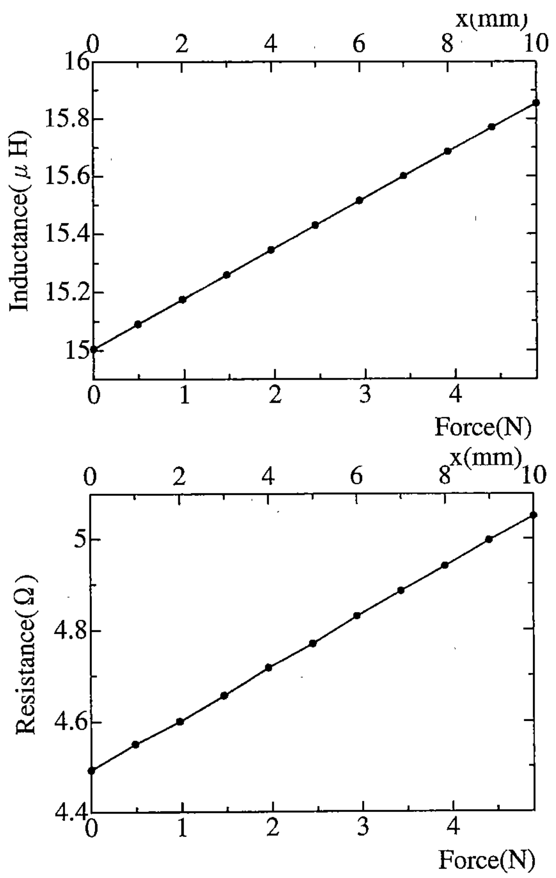


Fig. 7. Force characteristics of this sensor.

inserting into the coil results in the inductance increasing. The approximate functions of the results are shown as follows:

$$\begin{cases} L = 0.085x + 15.0\ \mu\text{H} \\ R = 0.056x + 4.49\Omega \end{cases} \quad \cdots\cdots (5)$$

which indicates better linear relations. The larger the force is, the deeper the iron core inserts, with the inductance and resistance curves going up.

2.3 Temperature Measuring The coil is wound by a fine copper wire. Copper resistance is often used to measure the temperature. The characteristics of copper resistance are the low price, the high degree of purity, the long durability and its great temperature coefficient. The relationship between the copper resistance and the temperature is some linear one, which can be shown as

$$R_t = R_0(1 + \alpha \times T) \quad \cdots\cdots (6)$$

where R_t is the resistance when the temperature T equals t, R_0 is the resistance when the temperature T equals 0 ℃, and α is the temperature coefficient of copper resistance.

Although the resistance of copper has so large an affection on the temperature, the inductance of the coil has little such an affection. That is to say,

$$\begin{cases} L_3 \neq L_3(T) \\ R_3 = R_3(T) \end{cases} \quad \cdots\cdots (7)$$

The inductance does not follow the temperature. (This can be seen from the experimental results later.)

To sum up, the inductance of the sensor is the function of the material conductivity ρ, permeability μ and the spring compress quantity x. The resistance of the sensor is the function of the material conductivity ρ, permeability μ, the spring compress quantity x and the temperature T.

$$\begin{cases} L = L(\rho, \mu, x) \\ R = R(\rho, \mu, x, T) \end{cases} \quad \cdots\cdots (8)$$

3. Experimental Methods, Results and Discussions

3.1 Temperature Measuring Fig.8 shows the temperature effect on the inductance and resistance of the sensor. Experiments were carried out with the measurement frequency of the LCR meter being set up to 100 kHz. The approximate functions of the results are as follows:

$$\begin{cases} L = -0.00130T + 15.0\ \mu\text{H} \\ R = 0.0158T + 4.10 \\ \quad = 4.10(1 + 3.85 \times 10^{-3}T)\ \Omega \end{cases} \quad \cdots\cdots (9)$$

From (6) and (9), we have

$$\begin{cases} R_0 = 4.10\ \Omega \\ \alpha = 3.85 \times 10^{-3} \end{cases} \quad \cdots\cdots (10)$$

The inductance of the sensor decreases 0.2% while the resistance increases 9.2% when the temperature varies

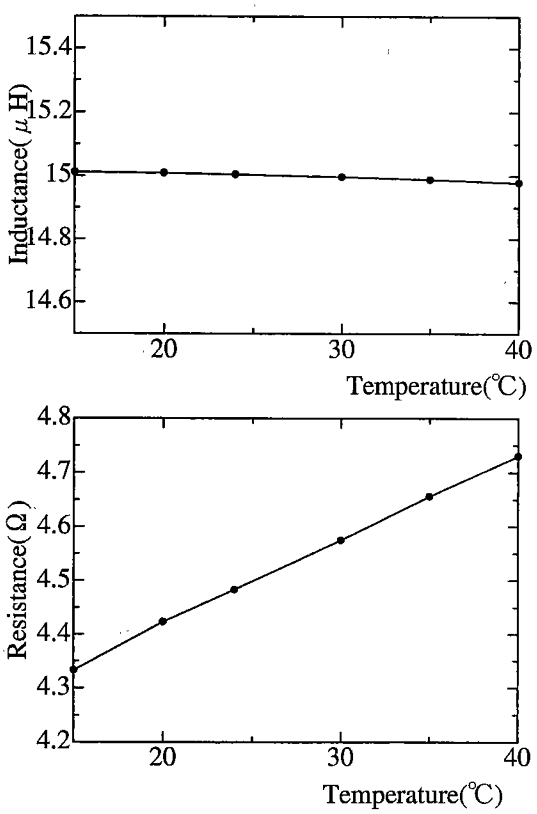


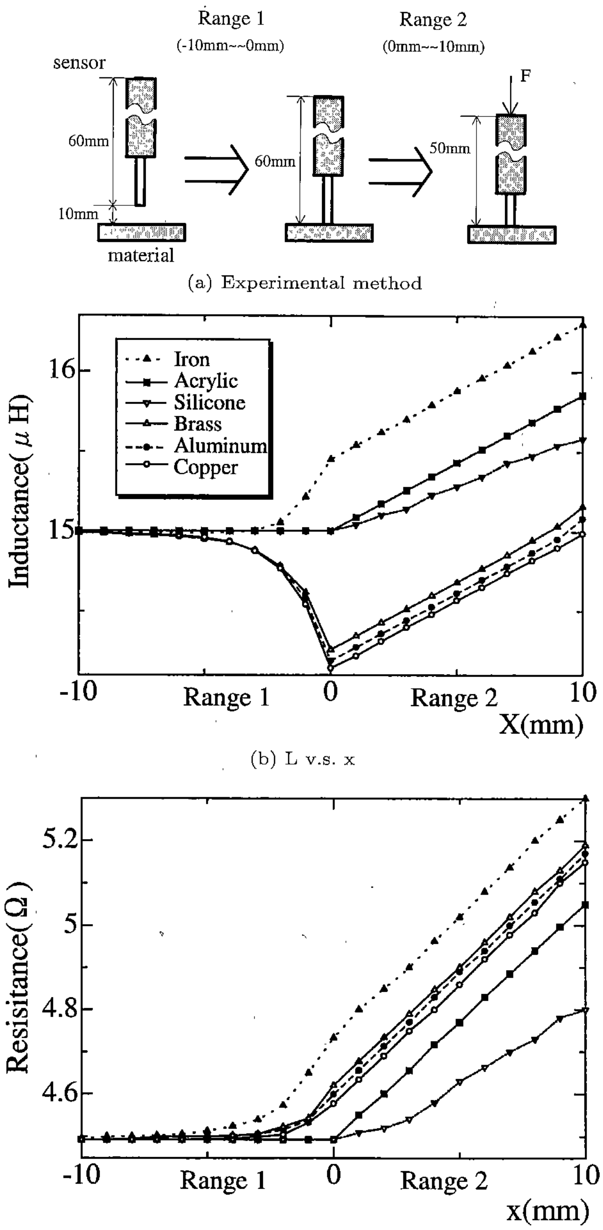
Fig. 8. Temperature measurement.

from 15 ℃ to 40 ℃. Obviously, the influence of the temperature on the resistance is much greater than that on the inductance. Variations in inductance are so small that they can be neglected.

3.2 Material Variety Discriminating and Character Analyzing Material discriminating carries character analyzing through without stopping, but the material variety discriminating is the prerequisite for character analyzing. The whole methods are as follows:

First, let the sensor be perpendicular to the surface of the material to be measured and the bottom of the sensor stays 10 mm away from the material. Second, move the sensor towards the material with one stop every 1 mm until the sensor touches the surface of the material, meanwhile, at each point the inductance and resistance of the coil are observed. As soon as the sensor touches the material surface, material variety discriminating process finishes. Then exert some force on the top of the sensor resulting in the spring inside being compressed. The force was exerted continuously with one stop as the spring's compress quantity increasing 1 mm from 0 mm to 10 mm and at each point the inductance and resistance of the coil are observed. The experiments were carried out using a robot hand with iron, brass, aluminum, copper, acrylic and silicone samples. All of these materials are formed as a rectangular plate of 3 cm by 3 cm with 1 cm thick. During the experiment, the environment temperature was set up to 24 ℃ and the working frequency of LCR meter 100 kHz.

Fig.9 shows the experimental method and results where the x-axis range was set from -10 mm to 10 mm.



(a) Experimental method

(b) L v.s. x

(c) R v.s. x

Fig. 9. Experimental method and results.

The range from -10 mm to 0 mm means the distance between the sensor bottom and the material to be measured before their contact and this range is defined as Range 1. The range from 0 mm to 10 mm means the spring's compress quantity after their contact and this range is defined as Range 2. Table 1 shows a relative variation rate contraction between the inductance and resistance values. In both Range 1 and Range 2, the contraction has been done. In Range 1, the algorithms of the relative variation value γ_L and γ_R are defined as

$$\begin{cases} \gamma_L = \dfrac{L(x=0) - L(x=-10)}{L(x=-10)} \times 100\% \\ \gamma_R = \dfrac{R(x=0) - R(x=-10)}{R(x=-10)} \times 100\% \end{cases} \cdots (11)$$

In Range 2, the algorithms of the relative variation

Table 1. Relative variation value contraction.
(T=24 ℃)

Material variety	Inductance relative variation value γ_L (%)		Resistance relative variation value γ_R (%)	
	in Range1	in Range2	in Range1	in Range2
Iron	+3.0	+5.5	+5.3	+12.0
Brass	-5.0	+6.3	+2.8	+12.3
Al	-5.4	+6.3	+2.4	+12.4
Copper	-5.7	+6.0	+1.9	+12.5
Acrylic	0	+5.7	0	+12.4
Silicone	0	+4.0	0	+6.8

value γ_L and γ_R are defined as

$$\begin{cases} \gamma_L = \dfrac{L(x=10)-L(x=0)}{L(x=0)} \times 100\% \\ \gamma_R = \dfrac{R(x=10)-R(x=0)}{R(x=0)} \times 100\% \end{cases} \quad \cdots\cdots (12)$$

In Table 1 the results are calculated from the experiment results shown in Fig.9 by using equations 11 and 12. The experiments were done at 24 ℃. If the temperature varies, the results in Table 1 will change in resistance measurement. Experiment results show that with the increasing of the temperature, the resistance relative variation value γ_R will decrease both in Range 1 and Range 2.

In Range 1, different materials have different influence on the sensor. In inductance measuring, concerning to iron, for it has a significantly large permeability μ, iron makes the inductance of the sensor increase. However, for other metals, which have nearly equal permeability, the conductive ρ plays an important role in material discriminating. All of these metals make the inductance decrease. In resistance measuring, both ferrous and non-ferrous metals cause the sensor's resistance increase. Non-metal materials can not make the inductance or resistance vary because of the lack of eddy current effect on the sensor.

In Range 2, all the hard materials' diagrams can be approximately regarded as straight lines, because the variety of metal has no influence on the sensor any more, but every straight line has different starting point. Concerning with soft materials, which are generally non-metal, they have no such a straight-line relationship and their values are smaller than other hard non-metal materials.

From the above analysis, it is clear that in Range 1 material variety is discriminated and in Range 2 character analysis is made.

3.3 Hard Material Surface Shape Detection

In this measurement function, the experimental results in Range 2 in Fig.9 (b) and (c) are used as reference. As described before, if the material to be measured is hard but has a curved surface, when a force is exerted to the top of the sensor and then the sensor is moved horizontally, values at different points will be obtained. By contracting these measured values and the results in Fig.9, the spring's compress quantity at each point will be known, and then, curved or plane surface of the material can be detected. However, the prerequisite for this function is the known material variety which is done before the sensor contacts the material. The essential conditions for this experiment are:

(1) The moving direction of the sensor top should be parallel to the bottom of the material to be measured.

(2) The length of the sensor must be kept from 50 mm to 60 mm during the whole measuring process.

In our experiment, shapes of curved (with a diameter of 30 mm) surfaces were used from three materials, i.e., iron, aluminum and acrylic. Fig.10 (a) shows the method. The line which is 70 mm higher than the bottom of the material is regarded as the sensor top line. The surface during the interval from -10 mm to 10 mm were tested according to the following steps:

(1) Allow the sensor be perpendicular to the bot-

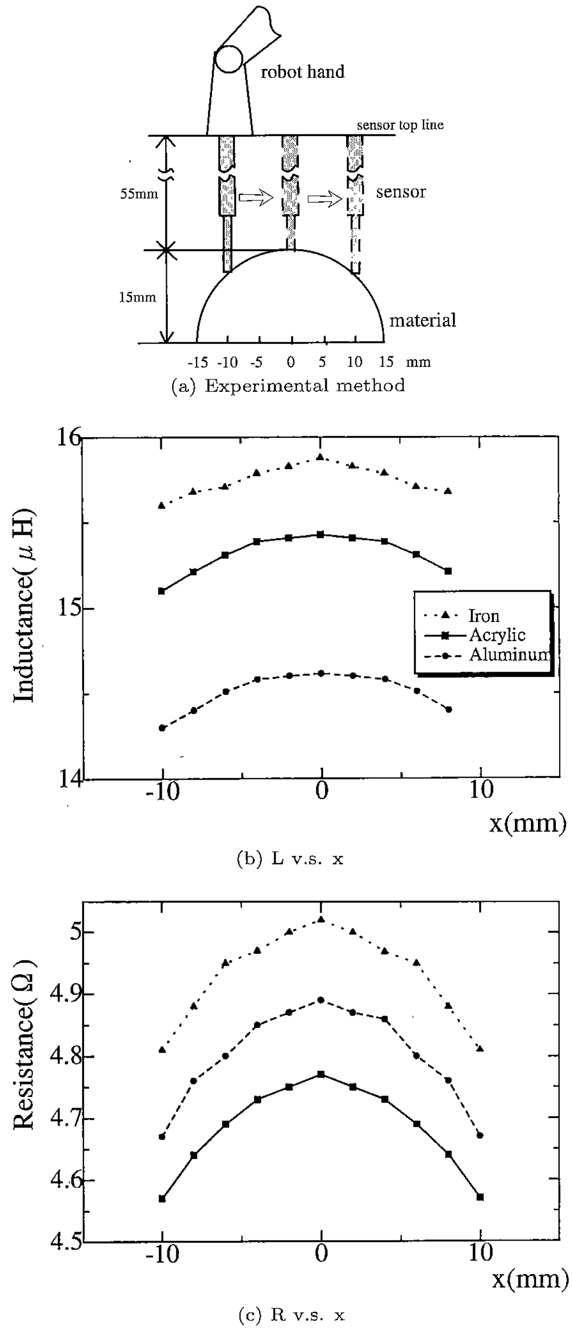


Fig. 10. Hard material shape detection.

tom of the material at x=-10 mm (the left extremity of the test interval), make the robot hand come down until the sensor's top arrived at the sensor top line, and then observe the outputs of the sensor.

(2) Make the robot hand come up by 5 mm, move the robot hand horizontally 2 mm to the right, make the robot hand come down by 5 mm and then observe the relative inductance and resistance at that position. These series of actions are done for 10 times.

In the actual situation, the distance between the sensor top line and the material bottom may be difficult to obtain, the distance should be adjusted for several times until we get the optimum distance for the shape detection.

Fig. 10 (b) and (c) show the experimental results with different materials. During the experiment, the environment temperature was also set up to 24 ℃ and the working frequency of LCR meter was 100kHz.

4. Conclusions

A pencil-shaped multi-functional tactile sensor that is able to discriminate the material to be measured and analyze some surface properties is proposed. The central and sensing part of this sensor is a coil with a diameter of 3 mm. Based on the special structure of the sensor and the ingenious measuring methods, the authors realized the objective to measure more than one quantities with a single sensor. By analyzing the sensor's outputs, three material properties can be obtained according to the following measurement steps:

(1) Measure the environment temperature from the sensor's resistance output.

(2) Determine the material variety by synthetically considering the inductance and resistance outputs.

(3) Analyze the material surface shape with the variety known.

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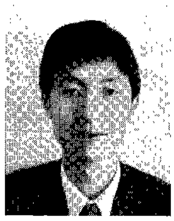

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