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PREFACE

The following papers were presented at the 1991 International Congress and Exposition during the five sessions on Sensors and Actuators. Thanks are extended to all the authors for their contributions. The diversity and excitement of this rapidly developing area is apparent in their contributions. To each of you who is interested in this area, I extend my invitation to participate in future sessions.

Stephen J. Citron
Sessions Organizer & Chairman
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910269

Long Life Potentiometric Position Sensor — Its Material and Application

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ABSTRACT

Recently various kinds of position sensors have been used in automotive subsystems which include Electronic Fuel Injection, Active Suspension and Exhaust Gas Recirculation (EGR). Because a potentiometer has a simple structure in which a brush slides on a resistor surface, it has many advantages such as high temperature applications, low cost, high signal level and almost infinite resolution compared to other kinds of position sensors that are magnetic or optical in nature. The potentiometer is considered to have the highest potential for a position sensor.

However, conventional potentiometers sometimes lose their linearity after use under severe conditions such as engine vibration (dither). They can endure only tens of millions of cycles of dither. This linearity error is thought to result from the following process:

1st stage: The resistive element wears by numerous cycles of slides.
2nd stage: The wear debris are generated and are deposited between resistor and brush.
3rd stage: Contact resistance increases as the contact area between resistor and brush decreases, since debris act as an insulator.

In order to prolong the sliding life of a potentiometer, the wear of both the resistive element and the brush must be reduced.

Carbon resistors consist of binder resin, carbon black, and some fillers that reinforce the resistors. By choosing these materials well, we have succeeded in developing a potentiometer that has a lifetime of more than one billion cycles of dither, preserving the initial linearity throughout this period of use.

INTRODUCTION

Automotive electronic control systems using microprocessors have increased rapidly in numbers sold and in complexity, in accordance with the recent advances in electronics technology. In the 1960's, the electronic ignition system was introduced, using primarily transistors and diodes. In the 1970's, using integrated circuits and microcomputers, various kinds of automotive electronic subsystems were introduced.

As the use of microcomputers and microprocessors progresses, the number and types of electronic subsystems will increase in response to the needs of safety and convenience of passengers, the increased reliability of mechanisms, the need for energy saving and the need for low environmental pollution in the future.

Intermediate-priced and economy automobiles are also predicted to include these systems, which are now limited to luxury cars. At that time, sensors and actuators will play an important role, with high reliability and low cost desired.

Table 1 Comparison of position sensors.

	TEMP -40°C ~+125°C	LIFE 1 mill	LINE 2%	RESO 0.5%	S/N	COST
POTENTI-OMETER	1	2	1	1	1	1
HALL EFFECT	2	1	1	2	4	4
INDUCT-ANCE	1	1	2	2	3	3
ENCODER	3	1	2	4	3	4

1: EXCELLENT 2: GOOD 3: FAIR 4: POOR

In general, automotive sensors are used under extremely severe conditions compared to a typical electronic component. For example, an in-engine vibration (dither) and the heat generated by an engine can cause heavy damage to these components in an under-the-hood environment.

For use as position sensors, potentiometers offer the potential of better quality, compared to other kinds of position sensors that are magnetic and optical in nature, since they have advantages such as high signal level, higher temperature capabilities and low cost. Table 1 shows the comparison of various kinds of position sensors.

However, as can be seen in Table 1, the potentiometer is inferior to other kinds of position sensors only with respect to operational life. This is because the potentiometer is of the contact type, and mechanical contact will necessarily wear out and eventually cause breakdown. Thus, the potentiometer would truly achieve the highest performance, if it were possible to improve the wear and breakdown resistance.

In this paper, the material improvement to achieve better wear resistance of the components of a potentiometer and the application of potentiometric position sensors are discussed.

1. POTENTIOMETER

The structure of the potentiometer is simple. The main components of the potentiometer are a resistive element, a brush and an axis or a shaft, depending on whether the potentiometer is a rotational type or a linear type respectively. An input voltage

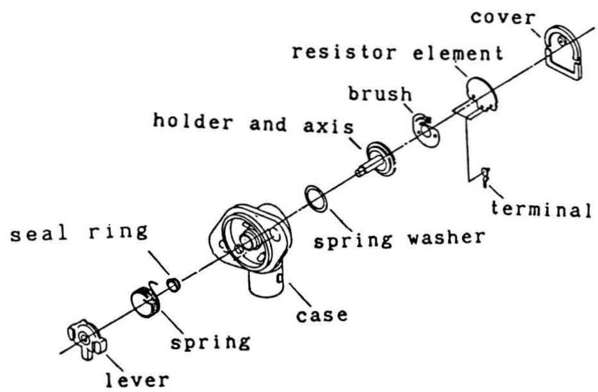


Fig. 1 A structure of a potentiometer for automotive sensor application.

is applied between two terminals of the resistive element called 1T and 3T, respectively. An output voltage is generated between 1T and a terminal of the brush (2T) corresponding to where the brush is positioned.[1] Fig. 1 shows the structure of a typical rotational-type potentiometer for a position sensor and its equivalent circuit.

Of the components, the brush and the resistive element play the most important role in determining the characteristics of the potentiometer. The resistive element, especially, is said to be the most important component in the potentiometer with regard to the sliding life and also with regard to resistance stability under conditions of environmental change.

Desired characteristics of the resistor are as follows:

(1) Should be stable under both short-term and long-term environmental changes such as temperature and humidity. For example, short-term resistance change versus temperature is specified by the Temperature Coefficient of Resistance (TCR).
(2) Should provide less wear to the resistor or less damage to the brush.
(3) Should be low in cost.
(4) Should be suitable for mass-production.

The resistive elements typically used in the industry are as follows:

(1) Wirewound resistor
(2) Carbon composition resistor
(3) Metal-glaze (cermet) resistor

Of these resistive elements, carbon composition resistors are the most widely used in both consumer and industrial applications.

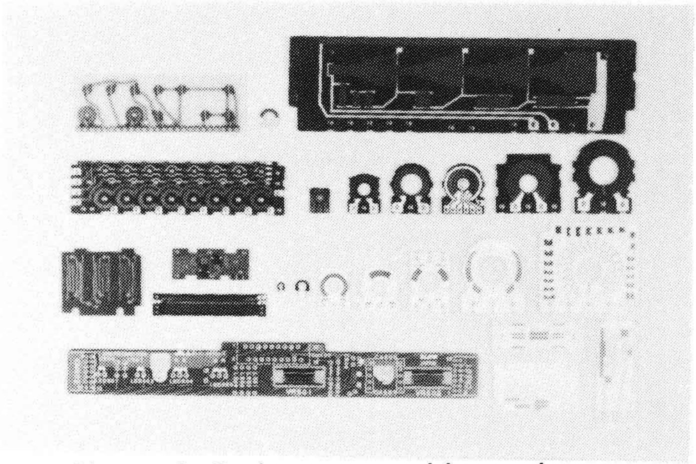


Photo. 1 Carbon composition resistor.

This is because of their high reliability, low cost and easy processing for mass-production.

Photo. 1 shows various kinds of carbon composition resistors.

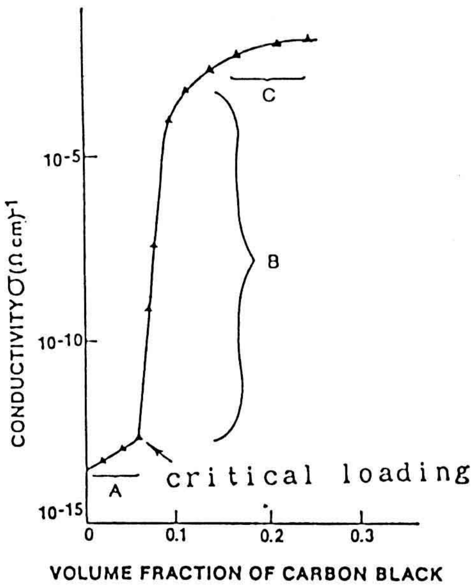


Fig. 2 A typical loading vs. conductivity curve.

2. MATERIAL OF CARBON COMPOSITION RESISTOR

2-1. ELECTRIC CONDUCTIVE MATERIAL

Usually carbon blacks and graphites are used as the electric conductive materials in the carbon composition resistor.

2-2. LOADING VOLUME

A loading volume of carbon blacks and graphites is an important factor in determining the resistivity and the electrical characteristics of the resistor. Fig. 2 shows a typical loading vs. conductivity curve of Nitrile-Butadiene-Rubber (NBR). At low loading of the carbon black (region A), the composition acts like an insulator. As the loading is increased, a critical loading is reached where the conductivity starts to increase rapidly as a function of loading (region B). At high loading, carbon aggregates are so tightly packed that the conductivity of the composition becomes high and stable (region C).[1)]

The loading volume of the carbon black to the carbon composition resistor is within region C. In region C, there are advantages of higher stability of resistance versus temperature, ohmic conductivity, higher wear resistance and less frequency dependence.

2-3. BINDER-RESIN

Since all the electrically conductive materials are powders, some binder material is needed in order to provide adherence to the substrate. For this purpose, thermosetting resins are commonly used, such as phenol-formaldehyde and epoxy.

The desired characteristics of a binder-resin are as follows:

(1) Should be soluble to solvents that have a boiling temperature above 200°C. Usually ethers and ketones are used.
(2) Should provide adequate viscosity for screenprinting.
(3) Change in the viscosity during storage should be acceptably low.
(4) Should provide more resistance against temperature changes and humidity.

Especially in the application of automotive position sensors under high temperature conditions, it is important to select higher heat resistance resins. These resins improve resistance stability and wear resistance under sliding conditions.

2-4. FILLER

Organic and inorganic powders that are added to carbon paste are called fillers. Three reasons for adding fillers are listed below:

(1) Improvement of resistance stability versus environment change. In order to improve humidity characteristics of the resistor, low moisture fillers are often added to the carbon paste. Inorganic powders such as silica, alumina, titanium-oxide and other metal-oxides are used for this purpose.

(2) Improvement of characteristics under sliding conditions. Polytetrafluoroethylene, molylbdenum disulfide and graphite are solid lubricants which are sometimes used as fillers in order to improve sliding characteristics.

(3) Improvement of stability of carbon paste. Carbon blacks and other electronic conductive powders have a characteristic of aggregating with each other during long periods of storage. As a result, the electronic conductivity of the carbon black chain decreases, and the potentiometer conductivity becomes lower. In order to prevent the aggregation of conductive powder and to stabilize the conductivity of the carbon paste, inorganic fillers are sometimes added to the carbon paste.

In our plant, the carbon composition resistor is manufactured by a screen printing process. In this process, the carbon paste is screen printed onto a phenolic-paper laminate, a ceramic or a plastic substrate, and then dried and cured in an oven at a temperature between 150°C and 300°C, depending on the binder-resin used. The electrical characteristics of the carbon composition resistor are measured, and the resistive elements are subsequently used in the potentiometer.

3. BRUSH

A brush is a key component due to its contact with the resistor surface and its pick up of the electrical signal. The important factors that are required of the brush are as follows:

(1) Should be chemically stable against humidity and corrosive gases such as NO_x and SO_2. For example, silver is a noble metal. However, it is known to form insulating silver sulfide when exposed to SO_2 gas. Thus, it is not a good idea to use silver as the brush material of a position sensor that is used under exhaust gas exposure.

(2) Should be less change in apparent contact area before and after sliding. This requirement exists because a change in the apparent contact area will increase the chance of catching debris from the resistor between the resistor surface and the brush. That makes contact resistance higher, as will be explained in detail later.

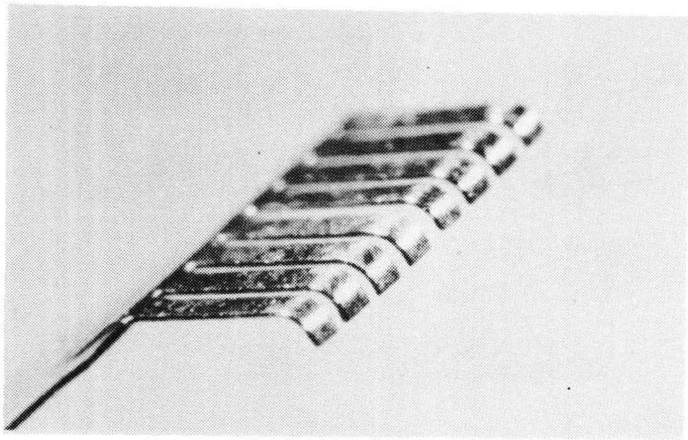


Photo. 2 Scratch-type brush.

(3) Should be low in cost.

(4) Should be less creep or fatigue against sliding. Creep and fatigue will cause the contact force to decrease and the contact resistance to increase.

(5) Should be less wear despite numerous cycles of sliding.

We use a scratch-type brush made of noble metal alloy as shown in Photo. 2. This is believed to be the most reliable brush available at this time, considering environmental stability, the needs to minimize material wear and the preservation of the contact force.

4. LUBRICANT

In order to improve the sliding characteristics between the resistive element and the brush, a lubricant such as grease or oil can be used. However, the use of grease sometimes significantly changes contact resistance, because a thickener (lithium soap, bentonite, urea, PTFE powder, etc.) in the grease works as an insulator between the resistor and the brush. Thus, it is best to use a lubricant oil which does not contain any thickener.

Various kinds of synthetic lubricant oils are shown in Table 2. In the case of automotive applications, temperature stability over a wide range (from as low as -40°C to as high as 200°C) is important. Commonly used lubricant oils are silicone, polyphenylether and fluorocarbon.

Table 2 Comparison of lubricant oil characteristics.

	viscosity index	low temperature flowability	oxidation stability	hydrolysis stability	load carrying capacity	additive efficiency
mineral oil	3	2,3	3	1	2	2,3
polyolefine	2,3	2	2	1	2	1
silane	2	2	3	1	3	2
silisic esther	1	1	2	4	3	3
silicone	1	1	2	2	4	4
polyphenyl-ether	4	4	1	1	3	2
fluorocarbon	4	3	1	2	2	4

1: EXCELLENT 2: GOOD 3: FAIR 4: POOR

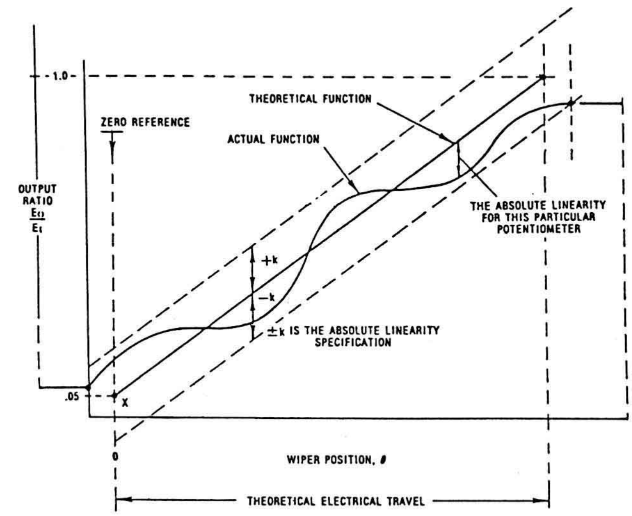


Fig. 3 Representation of an absolute linearity.

5.OPERATIONAL LIFE OF POTENTIOMETER

Since the potentiometer is a contact-type electronic device, eventual mechanical breakdown is inevitable. This is the reason why the potentiometer is considered inferior to other kinds of position sensors from a perspective of operational life as discussed earlier.

The mechanism of the breakdown and its prevention will be discussed in the next section.

5-1. LINEARITY

In our past experience, mechanical breakdown of the conventional potentiometer manifests itself as a linearity error. The linearity is defined as the output voltage deviation from the theoretical output curve in four ways: absolute, independent, zero based or terminal based. In the case of automotive position sensor applications, absolute linearity is the most effective and precise definition.

In the case of absolute linearity, the benefit exists that it is not necessary to adjust the holding position on assembling, because absolute linearity is defined theoretically or ideally. However, considerable cost is involved in manufacturing the potentiometer with an absolute linearity definition, since an accurate printing of the resistive element and accurate assembly is required. In this meaning absolute linearity is the most expensive of the four ways. Fig. 3 shows a representation of an absolute linearity specification.[2)]

When a linearity error occurs, the output voltage does not indicate the exact position of the shaft. Thus, when the linearity error increases to a critical extent, the potentiometer does not function well as a position sensor.

With regard to the resistive element, the reasons why the linearity error of the potentiometer becomes larger with use are:

(1) An increase in contact resistance due to the wear of the resistive element.

(2) Local wear of the resistive element because of dither or sensing some fixed positions.

Discussion of the above two factors follows:

(1) <u>An increase in contact resistance</u>- Between the brush and the resistor, there is a contact resistance. It is modeled as in Fig. 4.

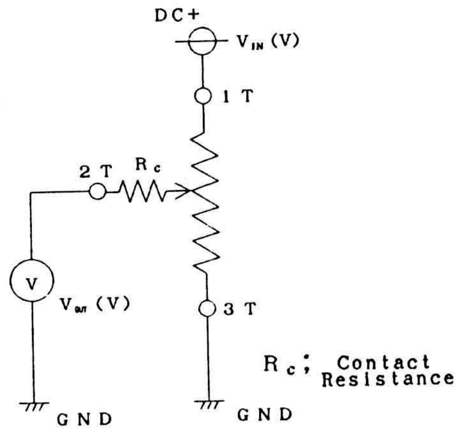


Fig. 4 Contact resistance in the potentiometer.

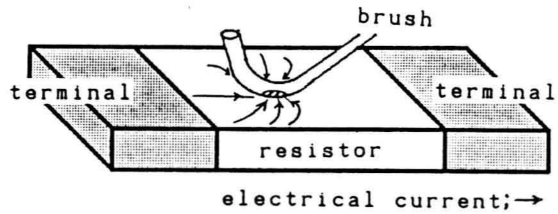


Fig. 5 Constriction resistance.

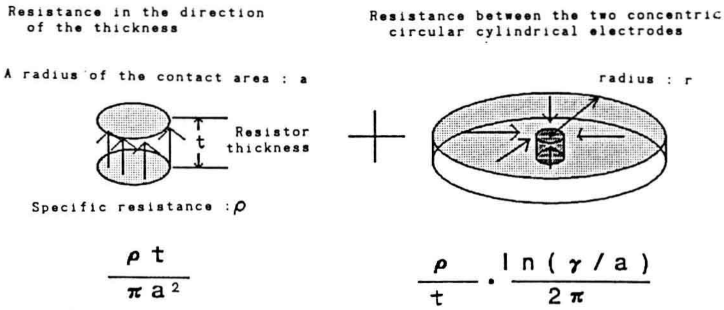


Fig. 6 Models of the constriction resistance.

A contact resistance is said to be a combination of a constriction resistance and a film resistance. The constriction resistance results from the narrowness of the effective conducting area of contact. On the other hand, the film resistance is caused by an object or a gap between the resistor surface and the brush.[3]

When the resistor surface and the brush contact each other, the constriction resistance to an electronic current is modeled as in Fig.5. Furthermore, the model includes two resistances. The first is the resistance between the two coaxial circular electrodes, and the second is the resistance in the direction of the resistor thickness as in Fig.6.[4]

Thus, the constriction resistance, R_1, is expressed by equation (1) below.

$$R_1 = \frac{\rho t}{\pi a^2} + \frac{\rho}{t} \cdot \frac{\ln(\gamma/a)}{2\pi} \tag{1}$$

where, ρ: specific resistance of the resistor.

t: thickness of the resistor.

r: =w/2, where w is the width of a resistor pattern.

a: radius of contact area.

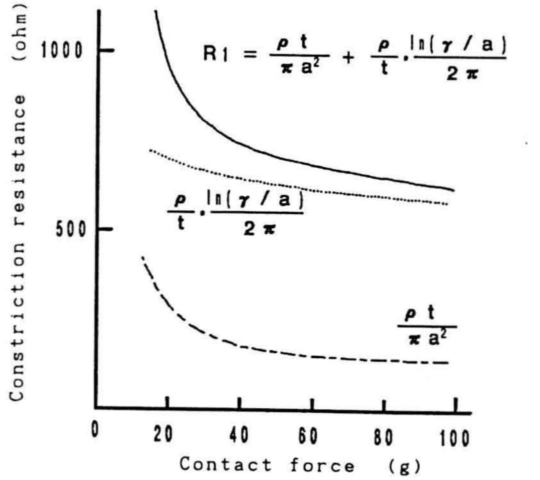


Fig. 7 Relationship between the contact force and the constriction resistance.

In the case of metal-metal contact, the average pressure of perfect plastic deformation is said to be three times greater than the elastic limit of the softer member. On the assumption that the same ratio between the average pressure of perfect plastic deformation and the elastic limit is formed in the case of the contact between brush and carbon composition resistor, the relationship between contact load and radius of the contact area is given by equation (2) below.[5]

$$a = \sqrt{\frac{W}{\pi p}} = \sqrt{\frac{W}{3Y}} \tag{2}$$

where, W: contact force

p: average pressure of perfect plastic deformation

Y: elastic limit of the softer member

From equations (1) and (2), the relationship between the contact force and the constriction resistance using the values below is shown in Fig. 7.

$\rho = 10^0\ \Omega \cdot cm$
$t = 10\ \mu m$
$\gamma = 1mm = 1 \cdot 10^{-1} cm$
$Y = 15 kg/mm^2$

The constriction resistance decreases as a function of contact force.

When a very thin layer of metal oxide or oil exists between two conductive materials contacting each other, the added resistance is

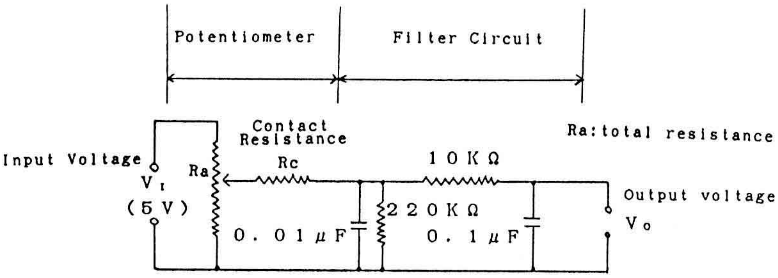


Fig. 8 Measuring circuit of the linearity.

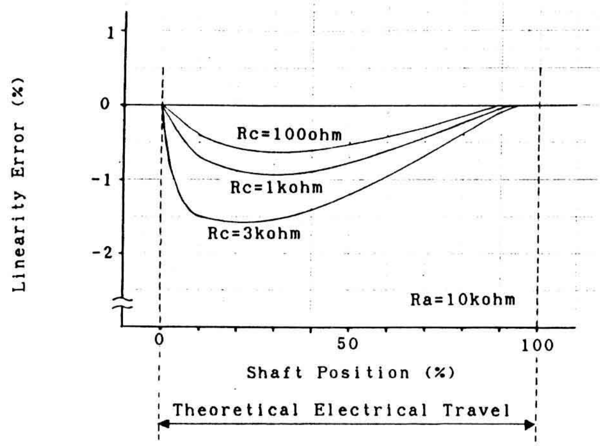


Fig. 9 Calculated linearity error due to the localized wear of the resistor.

called film resistance and is added to the constriction resistance. The film resistance, R_2, is shown in equation (3) below.[2)]

$$R_2 = \frac{\sigma}{\pi a^2} \tag{3}$$

Where, σ is a film resistance referred per unit area.

Because the contact resistance is a mixture of the constriction resistance and the film resistance, the contact resistance, R_c, is expressed by equation (4) below.

$$R_c = \frac{\rho t}{\pi a^2} + \frac{\rho}{t} \cdot \frac{\ln(\gamma/a)}{2\pi} + \frac{\sigma}{\pi a^2} \tag{4}$$

When the resistor wears out and generates debris on the surface of the resistor by numerous cycles of dither or sliding, the radius of contact area decreases and the film resistance increases. As a result, the contact resistance increases.

A calculation was performed to determine how much linearity error occurs relative to the contact resistant increase using Ohm's Law and Kirchhoff's Law as shown in Fig. 8. Calculated linearity error versus an increase in contact resistance is shown in Fig. 9.

(2) Localized wear of the resistor at the area of contact - In many position sensor applications, there are often reasons which cause a potentiometer to sense some fixed positions. For instance, in the case of an EGR valve position sensor, the position of the shaft is almost at either the position which corresponds to the EGR valve being closed or at the position corresponding to 50% of the total travel of the brush in our experiment.

In addition to the above, the engine generates a small vibration (dither) by its rotational motion, which causes the resistive element to fret. As a result, considerable wear can occur at these positions, and the resistivity increases because of a reduction in the cross-sectional area of the resistor at these positions of frequent contact.

In order to determine the influence of localized frequent contact, the linearity error was calculated.[4)]

In the case that half of the resistor (from A to B in Fig. 10) wears out due to frequent contact and its total resistance increases to x% of initial total resistance, the linearity error is calculated as in Fig. 10.[4)]

In a practical application, the linearity error occurs because of a mixture of the increase in the contact resistance and local wear of the resistor in a complicated manner. However, it is important to reduce the wear so as to minimize both the increase in contact resistance and the local wear of the resistor.

5-2. PREVENTION OF WEAR OF THE RESISTIVE ELEMENT

In order to prevent the wear of the resistor, important factors to consider in selecting the resistor material are as follows:

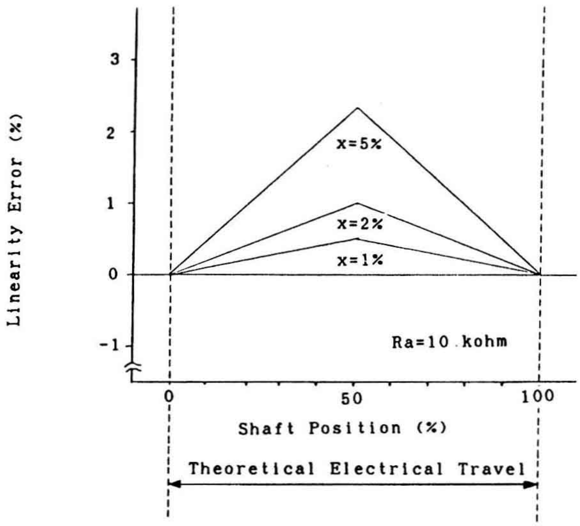


Fig. 10 Calculated linearity error due to the localized wear of the resistor.

(1) High temperature resistance binder-resin - Friction between the brush and the resistor generates heat of friction, which can damage the resistor chemically (burning) and physically (melting or softening).

(2) High load capacity filler - It is useful to add hard filler to the resistor that will accept the contact force of the brush and prevent pressure to the resistor itself.

(3) Excellent mechanical properties - S. B. Ratner et. al. said that the wear rate, V, of a viscoelastic material such as rubber is in inversely proportional to the hardness, H, strength at break, σ, and elongation at the break, ε, and is in proportion to the load, W, and frictional coefficient, μ, as in equation (5) below.[6]

$$V \propto \frac{\mu W}{H\varepsilon} \qquad (5)$$

Thus, it is important to use a tough, heat-resistive binder-resin and a hard filler in the resistor material to reduce the wear.

We have succeeded in developing a new type of potentiometric position sensor. As a result of careful design and material selection, these sensors have excellent wear-resistance and electronic properties.

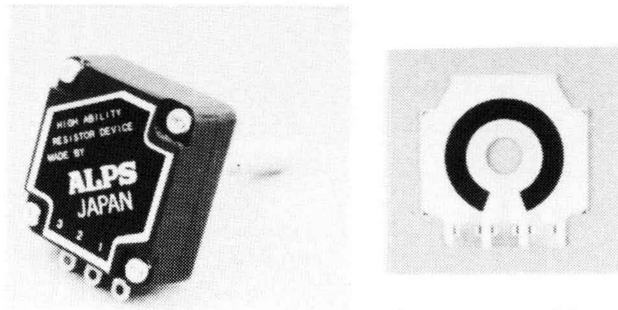


Photo. 3 The tested potentiometer and its resistive element.

6. SLIDING CHARACTERISTICS OF NEWLY DEVELOPED POTENTIOMETRIC POSITION SENSOR

The characteristics of the newly developed potentiometric position sensor under sliding conditions was tested. The tested sample is a rotational type of potentiometer with an electrically effective angle of 300°, a total resistance of 5 kohm, and a resistor thickness of 10 microns. The substrate is 96% alumina. Photo. 3 shows the appearance of the potentiometer and the tested resistive element.

6-1. MEASURING APPARATUS

The potentiometer is fixed by a jig and given a rotation or dither by a stepping motor. In order to measure the contact resistance, a constant DC current is applied between the two terminals 1T and 2T. The voltage between 2T and 3T is measured by using a measuring circuit as in Fig. 11.

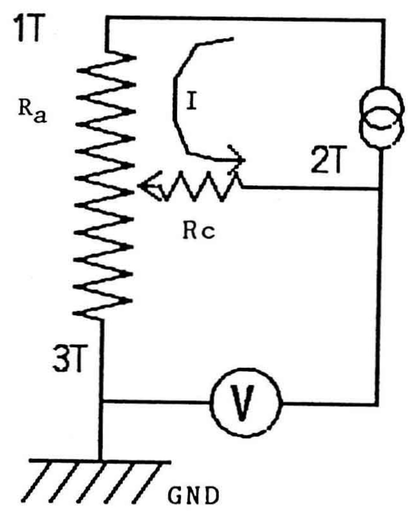


Fig. 11 Measuring circuit to determine contact resistance.

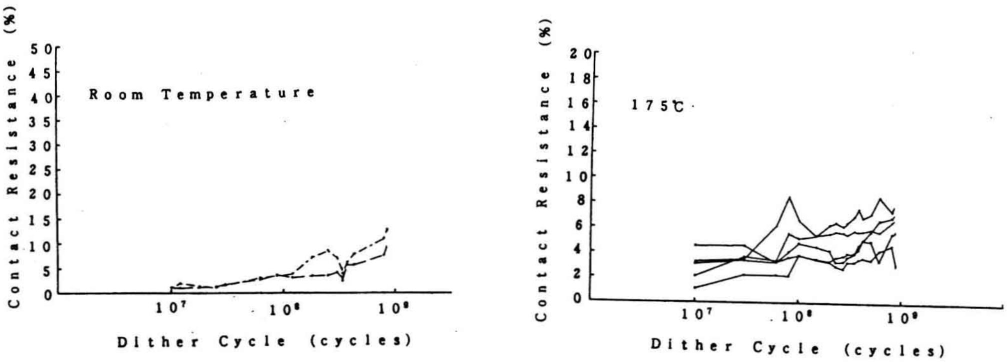


Fig. 12 A result of a dither test.

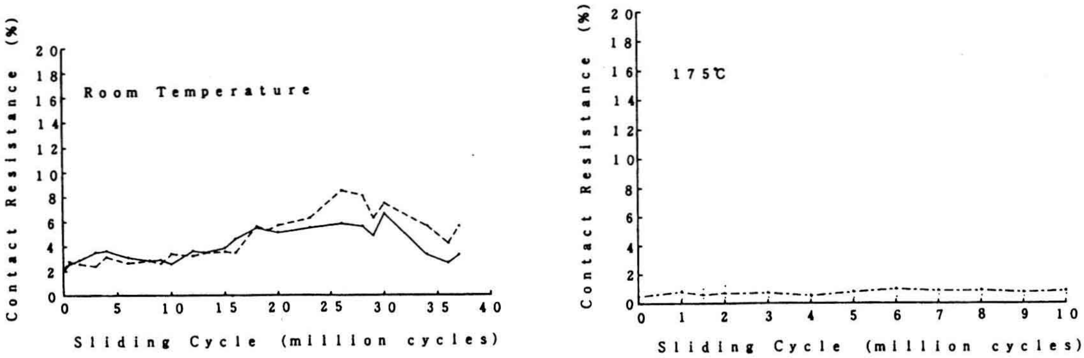


Fig. 13 A result of an operational test.

The contact resistance, R_c, as a function of total resistance, R_a, is calculated by equation (6) below.

$$R_c = \frac{V}{I} X \frac{1}{R_a} X 100 \quad (\%) \tag{6}$$

where, V: measured voltage between 2T and 3T (volts)
I: applied current between 1T and 2T (amperes)
R_a: total resistance of the potentiometer (ohms)

The influence upon the linearity of the contact resistance depends upon the resistance of the circuit and the position of the brush of the potentiometer. However, the critical contact resistance is estimated at 15% of the total resistance. Below this value, the potentiometer is expected to function well without any problems.

6-2. DITHER TEST

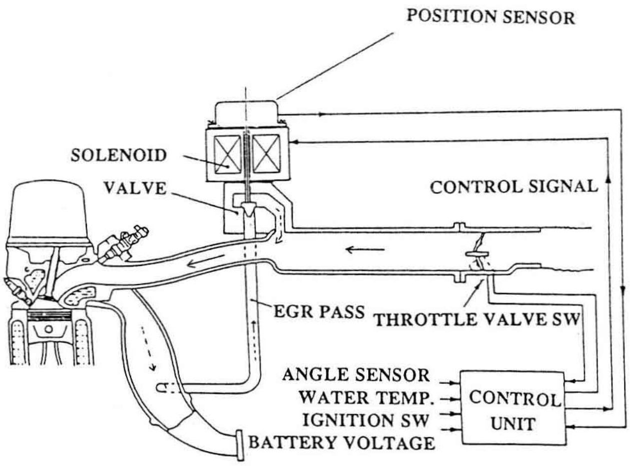
Fig. 12 shows the result of a dither test. Testing condition are as follows:

Ambient temperature:	Both at room temperature and at 175°C
Sliding distance:	0.5mm
Cyclic rate:	100 Hz
Average sliding speed:	0.36 km/hour
Sliding cycles:	1 billion cycles

The contact resistance of the potentiometer retains its initial value until 70 million cycles both at room temperature and at 175°C. After that, the contact resistance increases gradually, but does not exceed 15% of total resistance.

6-3.OPERATIONAL LIFE TEST

Fig. 13 shows the result of a 30° rotation operational life test. Testing conditions are as follows:



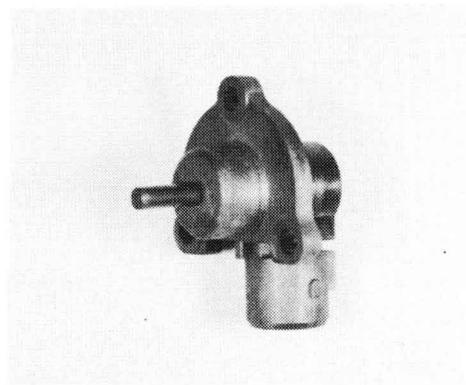


Fig. 14 EGR control system and its position sensor.

Ambient temperature:	Both at room temperature and at 175°C
Sliding angle:	30°
Cyclic rate:	4 Hz
Average sliding speed:	0.14 km/hour
Sliding cycles:	40 million cycles (175°C), 10 million cycles (room temperature)

The contact resistance of the potentiometer stay within 2% of its initial value at 175°C during the entire test. However, at room temperature the contact resistance keeps its initial value until 100 million cycles and then increases gradually, but dose not exceeds 15% of total resistance.

7. INTRODUCTION OF AUTOMOTIVE POSITION SENSORS

Some examples of position sensor applications using the long life potentiometer will soon be introduced.

7-1. EXHAUST GAS RECIRCULATION (EGR) VALVE POSITION SENSOR

EGR is a function that reduces NO_x in the exhaust gas by recirculating a portion of the exhaust gas to the intake manifold. An EGR valve position sensor is used to measure the lift height of the valve. The computer controls the valve lift height to the best position in accordance with the signal from the EGR valve position sensor. A schematic drawing of an EGR control loop, including our sensor, is shown in Fig. 14.

Because the EGR valve and sensor are located near the exhaust manifold and exposed to high temperature and severe dither, the EGR valve position sensor must withstand three hundred million dither cycles at a temperature of 175°C. That can be one of the most severe environments under which an electrical component may be expected to operate.

7-2.THROTTLE POSITION SENSOR (TPS)

A throttle position sensor is used in Electronic Fuel Injection and measures the angle of the throttle. Data is processed by the computer, and the appropriate angle of the throttle is decided. Fig. 15 shows the schematic drawing of an Electronic Fuel Injection Controller including the TPS.

The TPS must withstand one million cycles of sliding in its operational life at a temperature of 125°C at the present time. However, it is expected to need improved sliding characteristics, such as 3 million cycles of sliding life or 10 cycles of dither, in the application of drive by wire control in the future.