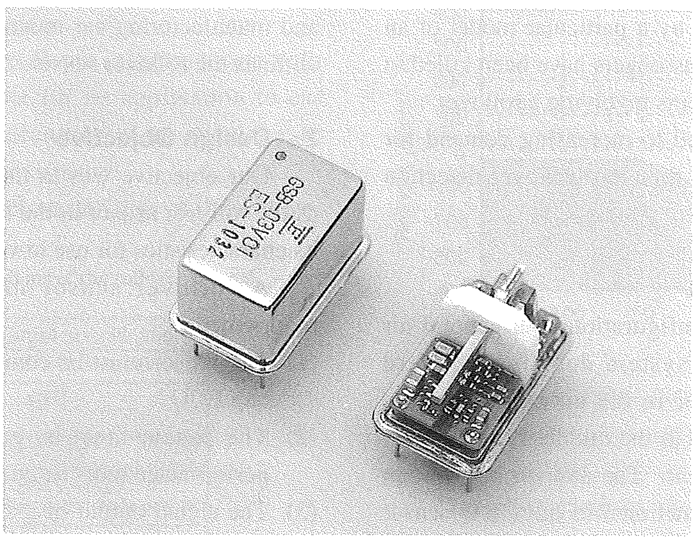
# Development of a Roll-over Sensor

● Masanori Yachi ● Katsufumi Morimune ● Hideaki kaino




## Abstract

Almost all the new automobiles come equipped with the air bag system: the device that will protect passengers in car collisions.

The air bag system is controlled by the "air bag ECU(Electronic Control Unit)".

We at Fujitsu Ten have been manufacturing and supplying air bag ECUs to Japanese auto makers for their domestic cars.

Lately, there have emerged new demands for much more reliable system than the air bag alone system.Such demand is very strong especially in the United States and Europe where there are lots of fatal car accidents reported daily: many of those ending up in overturning of cars with passengers inside.

As an answer to the market demand, Fujitsu Ten and Fujitsu Media Device Co.Ltd.(a Fujitsu Group member)have jointly developed a key device that will detect the roll-over of a car.The new-developed device is an angular velocity sensor(known as "the roll-over sensor"), which by far is superior in its compactness and accuracy to the counterpart products manufactured by competitors.

The following thesis explains a structural and functional overview of the roll-over sensor (as of 1998)and introduces features of its essential element technologies and evaluation method.

## 1. Introduction

### 1.1 Background

Since 1996, all new cars sold in Japan, the United States, and Europe come equipped with air bag systems as standard. In the United States, the reason is legal requirements; in Japan and Europe, it is a growing concern for safety.

Despite the presence of air bags, there have been many fatal accidents in which the occupants of a car have been crushed to death in rollovers in the United States and Europe. About a half of these fatal rollover accidents have been caused by a particular model of an American car. In Europe, passengers have been killed in about one-third of the accidents involving a rollover.

These statistics have led to increasing demand for the addition of a protective function (rollover detection function) to the present air bag system.

### 1.2 System Configuration

Figure 1 shows the configuration of a general air bag system. An air bag system detects a forward collision with the G sensor in the air bag electronic control unit (ECU) installed in the middle-front position in the passenger compartment. The new air bag system with a rollover detection function will have a G sensor that detects forward collisions and a rollover sensor that detects rollover in the air bag ECU. When a collision occurs, the system will activate a supplemental restraint system (SRS)(*1) that will include air bags for protecting occupants in a rollover.

The new air bag system requires a compact, low-priced rollover sensor that is appropriate for the present air bag ECU in terms of size and cost.

We have developed a compact, low-cost, high-reliability rollover sensor that makes use of an angular rate sensor being developed for navigation systems at Fujitsu TEN and technologies developed from designing and manufacturing car-mounted equipment. This paper outlines the rollover sensor.

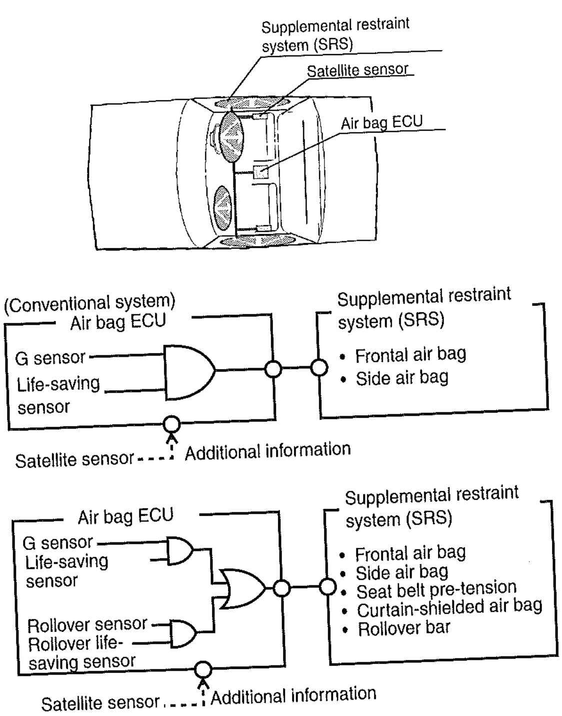



**Fig.1 Configuration of air bag system**

## 2. Design Objective

Our objective was to mount an angular rate sensor as the rollover sensor in the air bag ECU and to improve its characteristics for use in vehicles.

A rollover sensor must meet the following requirements:

(1) The sensor must be compact enough to fit in the air bag ECU.

(2) The sensor must be extremely reliable, and its performance must be guaranteed for 15 years.

(3) The signal output of a sensor mounted in a vehicle must not be affected by vibrations generated by the vehicle. (This characteristic is called the vibration resistance of the sensor.)

(4) The sensor must not be expensive.

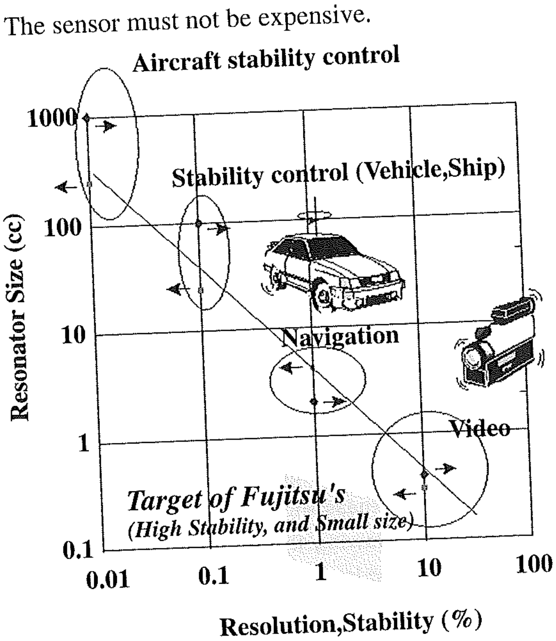



**Fig.2 Application of angular velocity sensor**

We developed the sensor jointly with Fujitsu Media Device, which has been developing sensing elements processe for refining materials. We wanted to develop a rollover sensor that has moderate accuracy and minimum size when compared to the angular rate sensors used for other applications shown in Figure 2.

Angular rate sensors are generally called gyroscopes, which are in widespread use. For example, expensive, extremely accurate gyroscopes are used for the inertial navigation systems of aircraft, and inexpensive, less accurate gyroscopes are used in video cameras to prevent unintentional movement of cameras during shooting.

Our intention was to develop a rollover sensor with a size and price appropriate for its application to car stability control with the accuracy of an angular rate sensor for navigation, but inexpensive.

Table 1 lists the target characteristics of the rollover sensor.

**Table 1 Target specifications of the rollover sensor**

| Item | Target specification |
|---|---|
| Supply voltage | 5±0.5 V (ratio metric) |
| Operating temperature | -40~85℃ |
| Offset voltage | 2.5±0.25V |
| Sensitivity | 6±0.6 mV/deg/s (Arbitrary setting must be possible.) |
| Frequency response | DC 30 Hz or more |
| Current consumption | 5 mA or less |
| Vibration resistance | 1 deg/s or less |
| Volume | 10 cc or less |

## 3. Development of New Technologies

### 3.1 Basic Configuration

#### 3.1.1 System

Figure 3 shows the algorithm for the rollover detection function.

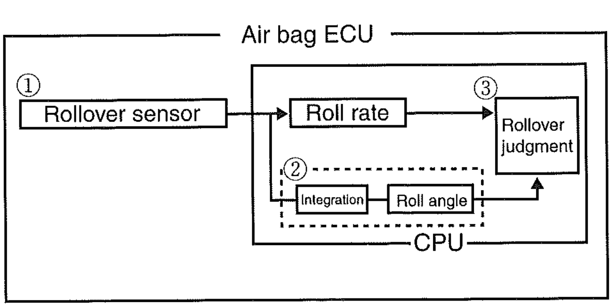



**Fig.3 Outline of detecting system**

(1) The rollover sensor detects the angular rate (roll rate) of a car.
(2) The roll rate is integrated to calculate the angle (roll angle) of the car.
(3) A two-dimensional map, such as the one shown in Figure 4, is drawn from the roll rate and roll angle. If a specific judgment area is exceeded, the car is judged to have rolled over.

The system judges rollover in these three steps, then activates various SRS mechanisms to protect the car's occupants.

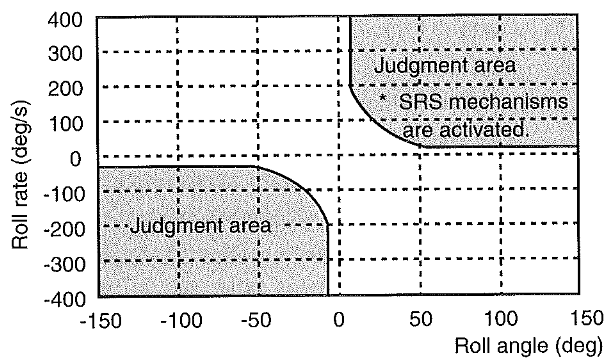



**Fig.4 Judgment map**

#### 3.1.2 Sensor

The rollover sensor consists of the four components shown in Figure 5.

(1) The sensing element detects the angular rate (Coriolis force *2) and converts it to an electric signal.
(2) The processing circuit drives the sensing element to extract the electric signal corresponding to the detected angular rate.
(3) The damping structure absorbs car vibrations. The stopper protects the sensing element from shocks such as would occur if it fell.
(4) The hermetically sealed metal casing, filled with an inert gas, protects the electric circuits formed by fine-pitch patterning and the sensing element from humidity.

These basic components, integrated in a single package, ensure that the level of the rollover sensor's performance and its reliability are sufficient for what the SRS requires to maintain the safety of the car's occupants.

*1 Supplemental restraint system (SRS)
Frontal air bags and side air bags are supplemental restraint devices. Main restraint devices are seat

belts. Auto makers often refer to air bags as "SRS air bags" in their catalogs.

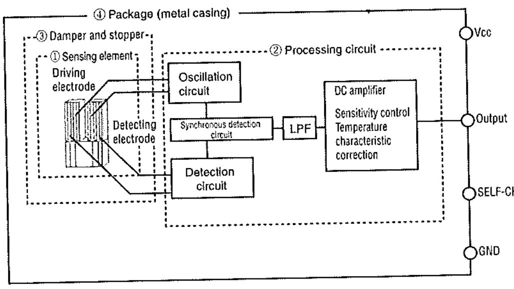



**Fig.5 Basic configuration of roll-over sensor**

*2 Coriolis force

The Coriolis force is an apparent force produced when an object rotates.

The force of inertia produced when an object rotates is the sum of the centrifugal force and the Coriolis force. When the mass of the object is m, rotation velocity is V, and angular rate is ω, the Coriolis force is expressed as 2mVω.

## 3.2 Design of the Sensing Element

### 3.2.1 Sensing-element requirements

The performance of the rollover sensor depends on the sensing element that converts the Coriolis force to an electric signal. To be adaptable for use in the environment inside a car, the sensing element must handle the following requirements:

(1) Wide range of operating temperatures (low drift)

The sensing element must have consistent characteristics throughout the temperature range from -40°C to +85°C.

The signal output from the rollover sensor is integrated and used as the value indicating a roll angle for rollover judgment. If signal components are inconsistent in relation to the temperature, the error in the integration result will be too large. The fluctuation of sensor output in relation to the temperature must be as low as possible (that is, the drift must be as small as possible).

(2) Low sensitivity to vibration (vibration resistance)

The sensing element must not detect any angular rate except that which indicates the car is rolling over.

The sensing element always receives other types of vibrating forces laterally and longitudinally. Although these other vibrating forces never cause a rotating movement (rollover) of the car, the sensing element still detects a certain level of vibration because of the sensor's structure. This characteristic has a trade-off relation to the high sensitivity and output described below.

For the structure of the sensor, see Section 3.2.4.

(3) High sensitivity and output

The sensitivity and output of the sensing element should be high enough to eliminate the need for amplification. If the output signal of the sensing element is amplified excessively by the processing circuit, the signal-to-noise ratio and signal reliability will deteriorate.

(4) Shock resistance

The sensing element must be strong enough to withstand the strong shocks that a car collision generates.

(5) Frequency

Frequency response of the sensing element must have a high natural frequency and be flat over a broad range.

The rollover sensor must detect each rollover symptom as quickly as possible because its operation affects human life. Its response must be about three times faster than the response of the sensors used in video cameras and navigation systems.

We developed the conversion mechanism that converts the angular rate detected by a fork-type oscillator using piezoelectric single crystals to an electric signal, the damping mechanism, and the entire structure of the rollover sensor.

### 3.2.2 Mechanism for converting angular rate to an electric signal

Figure 6 shows the typical types of angular rate detectors: Tuning-fork, triangular-prism, and cylindrical. These devices are generally called piezoelectric oscillating gyroscopes. A piezoelectric oscillating gyroscope has elements that are always oscillating along the same axis. If the gyroscope is turned, the elements begin oscillating along the axis perpendicular to the original axis because of the Coriolis force, and an electric potential is produced by the piezoelectric effect. Since the electric potential produced is proportional to the angular rate, the piezoelectric oscillating gyroscope can operate as an angular rate sensor. The elements used in piezoelectric oscillating gyroscopes are usually called oscillators.

A piezoelectric oscillating gyroscope is subject to unwanted noise called leakage, which is produced even when the gyroscope is not turning. The increase in sensing accuracy depends on how well the noise can be reduced. Another problem in a piezoelectric oscillating gyroscope is that it is easily affected by external vibration because its elements are themselves oscillating. Although the gyroscope must sense only rotating movements, it also easily senses the movements along other axes.

We chose the tuning-fork type of gyroscope from the typical types of gyroscopes for the rollover sensor.

**Typical types of piezoelectric oscillating gyroscopes**

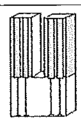
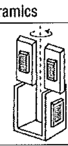
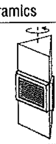
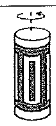
| Name | Our original gyroscope | Tuning-fork gyroscope | Triangular-prism gyroscope | Cylindrical gyroscope |
|---|---|---|---|---|
| Type | Tuning-fork | Tuning-fork (Watson type) | Tuning piece | Tuning piece |
| Material | $LiTaO_3$ crystal | Elinvar and ceramics | Elinvar and ceramics | Ceramics |
| Structure |  |  |  |  |
| Feature | Compactness: ◎<br>Sensitivity: ◎<br>Response: ○<br>Suitability to mass production: ○ | ○<br>○<br>○<br>× | △<br>○<br>△<br>△ | △<br>×<br>○<br>◎ |

**Fig.6 Typical example of voltage gyro**

The triangular-prism and cylindrical gyroscopes directly hold their vibrating parts. On the other hand, the tuning-fork type does not directly hold its vibrating parts and can keep their characteristics. The ordinary tuning-fork sensor is also called a Watson sensor. Figure 7 shows its structure. A piece of permanently elastic metal (Elinvar), which is relatively stable despite changes in temperature, is formed by a mechanical pressing into the shape of a tuning fork. A sheet of piezoelectric ceramic is attached to each of the four tuning pieces with epoxy-resin adhesive. The two lower tuning pieces are driving tuning pieces, and the two upper tuning pieces are detecting tuning pieces. A tuning-fork sensor with this structure, however, is not sensitive enough because resonance becomes weak if the right and left tuning pieces are unbalanced. Another problem of this type of sensor is that its characteristic change is unlikely to be linear because the piezoelectric ceramic itself is subject to hysteresis. For these reasons, this type of sensor requires gain and temperature compensation with large-scale electric circuits. Improving the accuracy of a tuning-fork sensor results in an increase in its size. It is difficult to make it small enough for incorporation into the air bag ECU.

For the rollover sensor, we developed an original tuning-fork type of oscillator using piezoelectric single crystals that has the advantages described below.

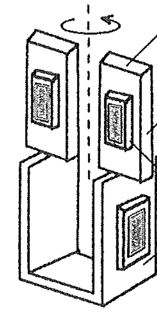



**Fig.7 Ordinary tuning fork-type sensor**

<Advantages of a tuning-fork oscillator using piezoelectric single crystals>

(1) Selection of sensing element

Single crystals of lithium tantalum trioxide ($LiTaO_3$) or crystals of lithium tantalum trioxide ($LiNbO_3$) are used as the sensing elements of the tuning-fork oscillator so that it will be compact, yet very sensitive.

(2) Process for producing a tuning-fork oscillator

The oscillator is suitable for mass production because the production process, including photoetching of electrode patterns on crystals, is equivalent to that used for semiconductors.

(3) Layout of electrodes

If the right and left arms have a symmetrical, balanced electrode structure, unnecessary output can be canceled out, and the linearity of output characteristics and thermal characteristics can be improved.

The following explains these advantages in more detail.

(1) Selection of sensing element

As shown in Figure 8, a tuning-fork oscillator using $LiTaO_3$ or $LiNbO_3$ has a higher Q value than a oscillator using piezoelectric ceramic, indicating sharper resonance. It also has a higher efficiency (electromechanical coupling factor) in the conversion from angular rate to electric signals than an oscillator using rock crystal.

In comparison with the Watson sensor, a tuning-fork oscillator can be made extremely compact.

The thermal influence of sensing elements on characteristics can be lessened by arranging the azimuth of crystals properly so that changes in temperature can be minimized.

These technologies related to sensing elements are original Fujitsu technologies and have already been applied to the SAW devices used in portable telephones. SAW devices have a 40-percent share of the world market.

Crystals of $LiTaO_3$ are currently used for the oscillator, but they will be replaced with $LiNbO_3$, which provide better thermal characteristics.

(2) Process for producing a tuning-fork oscillator

Each crystal is divided into wafers, then cut into the form of a tuning fork with a dicing saw. Electrodes to output signals are attached to the tuning fork by vapor deposition, and electrode patterns are formed by photoetching. The patterning technology for semiconductors is used because the accuracy of electrode patterns determines the characteristics of the element.

(3) Layout of electrodes

After analysis by the finite element method (FEM), we laid out the electrodes to minimize leakage. Detecting and driving electrodes are created on both the right and left arms (for a balanced electrode structure). This structure cancels out unnecessary output and improves the linearity of the output characteristics and thermal characteristics.

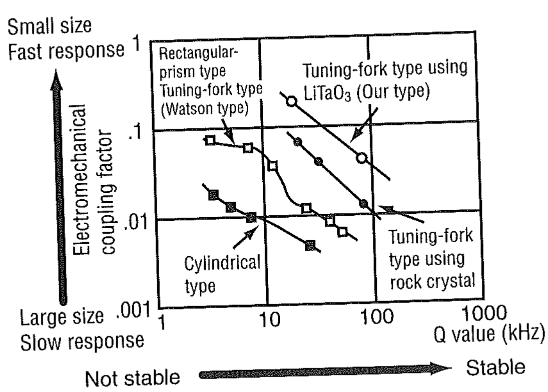



**Fig.8 Element characteristic**

### 3.2.3 Damping structure

We developed a new damping structure, shown in Figure 9, to make full use of the characteristics of an oscillator using piezoelectric single crystals described above and to improve the vibration resistance of the oscillator.

The theory of rollover sensor operation is explained first to make the explanation of the damping structure easier to understand.

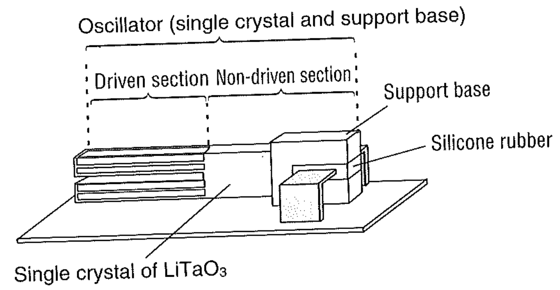



**Fig.9 Damping structure**

As shown in Figure 10, the arms of the oscillator continue to oscillate in the directions in which the arms move far away from on other. If the oscillator rotates, the arms begin oscillating in directions (detection directions) at right angles to the original oscillating directions because of the Coriolis force. The degree of the amplitude of the oscillation determines the sensitivity of the oscillator. When the amplitude is larger, the sensitivity is higher. Vibration and shocks are not inevitable for a car. The vibration and shocks the oscillator is subjected to can be reduced if the oscillator is rigidly attached, but rigid attachment causes sensitivity to drop. To lessen the effects of vibration and shocks without losing sensitivity, the following factors must be optimized:

(1) Elasticity (Young's modulus and hardness) of the support arm and the silicone rubber securing the oscillator

(2) Ratio of the driven and non-driven sections of the oscillator

(3) Relative sizes of the oscillator and support arm

We optimized all of these factors using the latest piezoelectric simulations, and developed the damping structure shown in Figure 9. Figure 11 shows the results of FEM analysis on the relation between the ratio of the driven and non-driven sections of the oscillator and leakage.

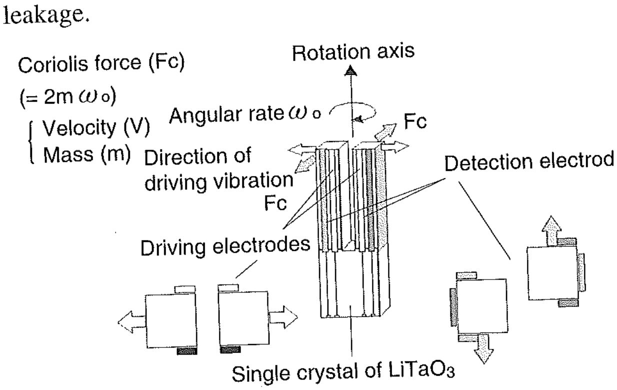



**Fig.10 Mechanism of detection**

When the deformation of the non-driven section is less, the deterioration of characteristics is also less even though the oscillator is supported over a large area.

Figure 12 compares the cross-talk resistance before optimization with that after optimization.

After optimization, the cross-talk resistance is expected to be at most about 10 times higher than that before optimization.

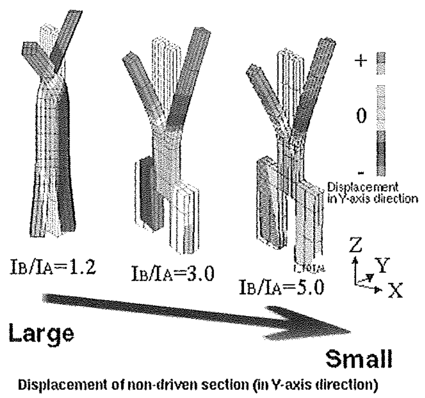



**Fig.11 FEM analysis**

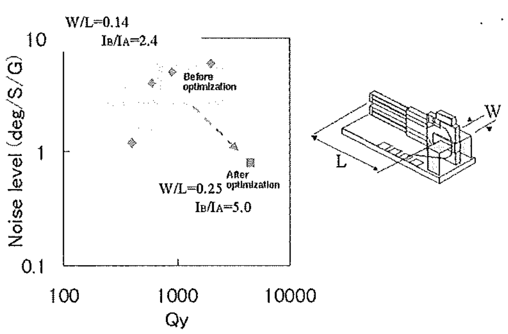



**Fig.12 Optimal design**

### 3.2.4 Structure of rollover sensor

The following were the requirements for the structure of the rollover sensor.

Because we started developing the sensing element while we were studying its specifications for mounting in a car, we were able to develop an original sensor structure for mounting in a car.

<Structural factors required for the rollover sensor>

(1) Single oscillator and processing circuit structure

(2) Control functions matching the oscillator and individual characteristics

(3) Hollow, air-tight package with excellent resistance to moisture

- The structure allows the oscillating parts of the element to move freely.
- Fine copper wires (single wires, 30 microns in diameter) are used for connections.

Figure 13 shows the structure of the rollover sensor.

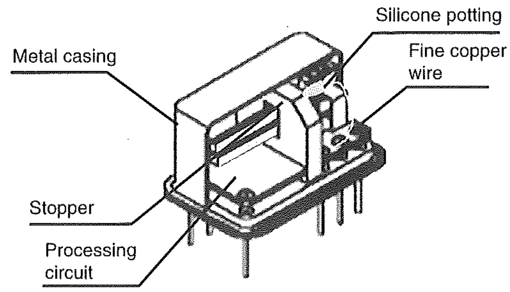



**Fig.13 Structure of roll-over sensor**

The processing circuit consists of a special IC that drives the sensing element and detects angular rate and a trimmable chip for electric control. The support arm for the oscillator is attached directly to a metal stem to prevent secondary resonance of the processing circuit board due to external noise. The oscillator is connected to the processing circuit by fine copper wires that do not disturb the oscillating motions of the sensing element. The copper wires are protected by silicone potting from vibration and shocks. A stopper that protects the sensor structure from shock if the sensor should fall is mounted. The guaranteed maximum protection against shock is 1,500 G. A general-purpose metal package that is already well-regarded in the market is used to meet the requirements of a hollow and air-tight structure and low cost. The package is filled with nitrogen gas to increase resistance to humidity and shocks.

## 4. Measurement of Characteristics

### 4.1 Outline of Measuring System

The measuring system must be extremely accurate to properly evaluate the performance and quality of the rollover sensor. In particular, measuring equipment that can measure the sensor's angular-rate detection performance with a high level of accuracy is necessary. Figure 14 shows the current measuring system.

With the rollover sensor secured on a rotary table with a jig, the measuring system turns the rotary table at a constant speed with a servo motor, and measures the sensor signal via a slip ring with an oscilloscope.

The thermostatic oven that evaluates the thermal characteristics of the rollover sensor has an air-tight structure to avoid condensation.

### 4.2 Performance Evaluation

The rollover sensor differs from other angular rate sensors in its excellent resistance to vibration and shocks. The reason is that it has been specifically designed for mounting in a car. The effects of the resonance of the rollover sensor on its characteristics must be evaluated to ensure that the rollover sensor is reliable.

The following evaluation systems, which have been used for Fujitsu TEN's air bag systems, can be used to evaluate the performance of the rollover sensor:

(1) Vibrator
Tests cross-talk resistance.

(2) Impact tester
Evaluates characteristics in excessive acceleration area.

The above measuring system and the two evaluation systems are used to measure the performance of the rollover system.

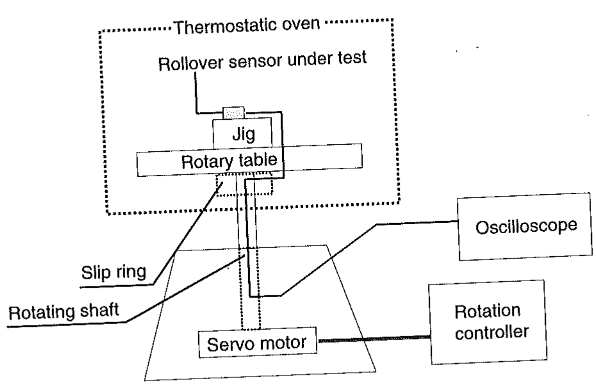



**Fig.14 Configuration of measuring system**

## 5. Specifications and Performance

Table 2 lists the typical performance characteristics that the rollover sensor must have.

The reliability evaluations listed in Table 3 have demonstrated that the performance characteristics are consistent. The rollover sensor also has the required reliability.

Because the rollover sensor has been designed with specifications for mounting in a car since its early development stages, it is suitable for the incorporation in the air bag ECU.

<Features of the rollover sensor>

(1) The rollover sensor can be made to conform to a wide range of specifications (sensitivity: 60 to 300 deg/S) by modification of the circuit constants.

(2) The rollover sensor has excellent response due to the compact element design.

(3) The rollover sensor can be used to measure power fluctuations in ratio-metric measurement.

(4) Since the rollover sensor has excellent cross-talk resistance, there are no limitations on how the air bag ECU is attached.

We expect that demand for vibration resistance will be more exacting in the future.

We believe that the vibration resistance in the current car-mount specifications will have to be increased about five times. To achieve this goal, not only the structure of the rollover sensor but also the overall system will have to be reviewed.

**Table 2 Specifications of rollover sensor characteristics**

Vcc=5.0V : Operating temperature: -40 to +85 °C

| Item | MIN | TYP | MAX | Unit | Note |
|---|---|---|---|---|---|
| Offset voltage | 2.25 | 2.50 | 2.75 | V | Arbitrary setting possible |
| Sensitivity | 5.40 | 6.00 | 6.60 | mv/deg/S | Arbitrary setting possible |
| Frequency response | 0 | | 30 | Hz | Arbitrary setting possible |
| Nonlinearity | -1 | | 1 | %FS | |
| Current consumption | | 6 | | mA | |
| Volume | | 2.6 | | cc | |

[Sensitivity characteristics]

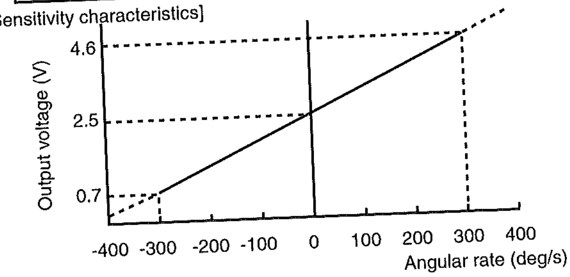



**Table 3 Reliability evaluation**

| Evaluation objective | Evaluated items |
|---|---|
| Mechanical strength | Total of seven items, including high/low-temperature operation durability test, operation durability test, drop test, and high/low-temperature vibration test |
| Environmental resistance | Total of 15 items, including thermal shock test, high/low-temperature storage test, and high-temperature, high-humidity conductivity test |

## 6. Afterword

Joint development by Fujitsu TEN, with its experience in car-mounted equipment technology, and Fujitsu Media Devices Limited, with its experience in sensor element technology, has resulted in the possibility of mass-producing a rollover sensor based on Fujitsu TEN's custom specifications.

In Europe and North America, there is a movement for installing a rollover detection function in the air bag

ECU to improve car safety in 2000.

The rollover sensor is increasingly being seen as the key device, and each manufacturer is developing a rollover sensor that can be built into the air bag ECU.

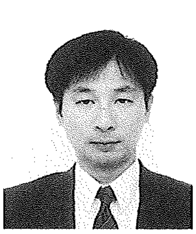
We have developed an extremely compact rollover sensor that meets the requirements for mounting in a car as well as the technologies required mount it. The technologies we used are already highly regarded.

We plan to construct a mass-production line for the rollover sensor in 1999 and to begin mass production in 2000.

We also plan to start development of a next-generation sensor that uses micro-machining technology.

Finally, we would like to express our gratitude to Fujitsu Media Device for the generous participation in this project.

## Authors



**Masanori Yachi**

Employed by Fujitsu Limited since 1987. Engaged in developing piezoelectric single-crystal devices. Currently assigned to the Piezo Electric Devices Department, Fujitsu Media Devices Limited.

**Katsufumi Morimune**

Employed by Fujitsu TEN since 1992. Engaged in developing electronic products for vehicles. Currently assigned to Engineering Department 1, Vehicle Electronics Division.

**Hideaki Kaino**

Employed by Fujitsu TEN since 1982. Engaged in developing electronic products for vehicles. Currently assigned to Engineering Department 1, Vehicle Electronics Division.