Paper

Development of the 3-axis Angular Velocity Sensor Using a Piezoelectric Element

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Operation of objects in 3-dimensional space can be expressed in terms of acceleration and angular velocity. Sensors to detect them are made by using micro-machining technology and ceramic technology. In the field of acceleration sensors, 3-axis acceleration sensors that detect acceleration in 3-dimensional space have already been marketed, and in the field of angular velocity sensors, piezoelectric 2-axis angular velocity sensors (1) have been developed. By applying such piezoelectric 2-axis angular velocity sensors, 3-axis angular velocity can be detected with the vibrator's velocity components in the directions of two axes, and the detection components of Coriolis force produced by angular velocity in the directions of two axes. By using this principle, we have succeeded in developing a 3-axis angular velocity sensor that detects 3-axis angular velocity with one detecting element. This report details the construction, detection principle, and detection circuit of the sensor, as well as the performance, including sensitivity, cross-axis sensitivity, and linearity.

Keywords: 3-axis, angular velocity, piezoelectric, Coriolis force

1. Introduction

Operation of objects in 3-dimensional space can be expressed as parallel motion and rotational motion. Parallel motion can be expressed as physical quantities, in terms of distance, velocity, and acceleration, while rotational motion can be expressed by the physical quantities of an angle, angular velocity, and angular acceleration. These physical quantities can be expressed by the mathematical relationship of differential or integration function.

Thus far, for detection of the six physical quantities of distance, velocity and acceleration (which represent parallel motion) and angle, angular velocity and angular acceleration (which represent rotational motion) only acceleration sensors and angular velocity sensors have been operational in micro-machining technology and ceramic technology. As a matter of course, acceleration and angular velocity are important physical quantities in detecting the motion of objects in 3-dimensional space. In the field of acceleration sensors, 3-axis acceleration sensors (2)-(4) of the piezoresistance type, capacitance type, and piezoelectric type have already been developed, and marketed by many companies. However, in the field of angular velocity sensors, 1-axis angular velocity sensors are predominant, though only a few 2-axis angular velocity sensors have been marketed.

Angular velocity is also a vector quantity like force and acceleration, and 3-axis angular velocity sensors are indispensable in detecting angular velocity accurately. Recently, on the market, needs for multi-axis angular velocity sensors are increasing gradually as is the case with acceleration sensors. We have conducted research into 3-axis angular velocity sensors (4) (5) to meet such demands. We wish to report on the piezoelectric 3-axis angular velocity sensor (6) we have developed recently, which is superior in sensitivity, cross-axis sensitivity, and linearity.

2. Detection Priciple of the 3-axis Angular Velocity Sensor

When an object having a mass moves at a certain velocity, angular velocity operates on the object with the result that an apparent force acts on it. This is known as Coriolis force. The 3-axis angular velocity sensor also uses Coriolis force. In the case of 3-axis angular velocity sensors, the vibrator, having a mass, is brought into rotational motion on the X-Y plane as shown in Fig. 1.

In this motion, the vibrator has a velocity component, Vx, in the X-axis direction at a certain instant, and has a velocity component, Vy, in the Y-axis direction in the next instant. As shown in Fig. 2, when the vibrator moves having velocity component Vy in the Y-axis direction, if angular velocity ωz in the Z-axis direction acts, Coriolis force Fx in the X-axis direction is produced, and if angular velocity ωx in the X-axis direction acts, Coriolis force Fz in the Z-axis direction is produced. Also, when the vibrator moves having velocity component Vx in the X-axis direction, if angular velocity ωy in the Y-axis direction acts, Coriolis force Fz in the Z-axis direction is produced. The relationship can be shown by the following expressions (1).

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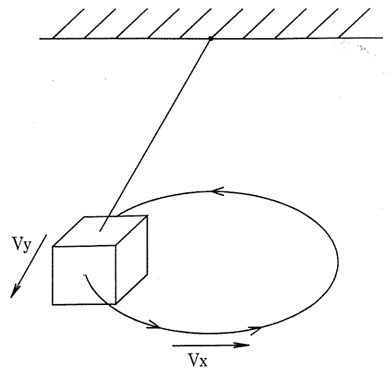


Fig. 1. Detection principle of the 3-axis angular velocity sensor

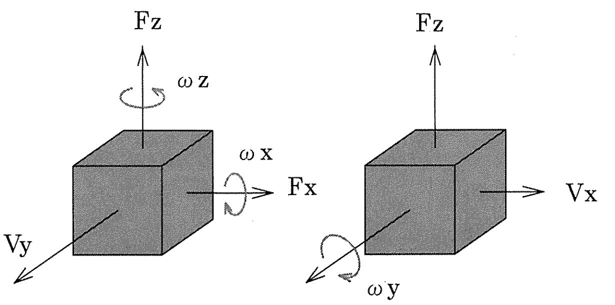


Fig. 2. Detection of ωx, ωy and ωz

$$\left.\begin{array}{l} \mathrm{Fx} = 2\,\mathrm{mVy} \times \omega \mathrm{z} \\ \mathrm{Fz} = 2\,\mathrm{mVy} \times \omega \mathrm{x} \\ \mathrm{Fz} = 2\,\mathrm{mVx} \times \omega \mathrm{y} \end{array}\right\} \cdots\cdots\cdots (1)$$

This expression shows that the angular velocity components (ωx, ωy, ωz) of three axes can be detected by detecting Coriolis force (Fx, Fz) in the directions of two axes while giving velocity components (Vx, Vy) in the directions of two axes by bringing the vibrator into rotational motion on the X-Y plane.

The 3-axis angular velocity sensor we have developed recently uses the so-called piezoelectric effect of piezoelectric ceramic; principle on which distortion occurs if voltage is applied, and charge occurs if distortion is given. The piezoelectric effect of the piezoelectric element is used for both circular motion within the X-Y plane, and detection of Coriolis force in the X-axis direction and the Z-axis direction. Since drive and detection are essential to angular velocity sensors, it can be said that the piezoelectric element is one of the suitable materials for angular velocity sensors.

3. Influence of Centrifugal Force on Coriolis Force

The error by the centrifugal force may arise on this element where external angular velocity acts on the same axis as the rotation axis of the vibrator. The following discusses the relationship between centrifugal force and Coriolis force.

3.1 When the Rotation axis of the Vibrator and the Rotation axis of the Input are in Complete Agreement As in Fig. 1 and Fig. 2, assume that the vibrator is rotating at angular velocity Ω around the Z-axis. With this rotation, when the vibrator passes on the −X-axis, centrifugal force −f1 acts in the X-axis direction. With the vibrator rotated 180 degrees, that is, when it passes on the +X-axis, centrifugal force +f1 acts in the X-axis direction. In this state, assuming that angular velocity ωz acts around the axis in complete agreement with the rotation axis of the vibrator, when the vibrator passes on the −X-axis, Coriolis force −Fx and centrifugal force −f2 in the X-axis direction are newly produced with angular velocity ωz. With the vibrator rotated 180 degrees, Coriolis force +Fx and centrifugal force +f2 in the X-axis direction are newly produced with angular velocity ωz. This state is shown in Fig. 3.

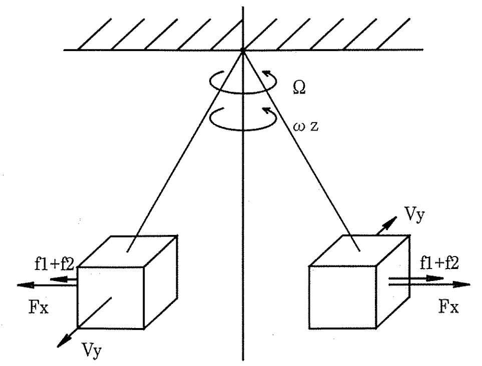


Fig. 3. Influence of centrifugal force when the rotation axes of Ω and ωz are in complete agreement

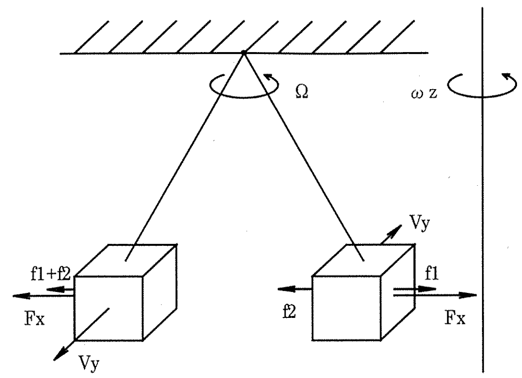


Fig. 4. Influence of centrifugal force when the rotation axes of Ω and ωz are not in agreement

When the vibrator passes on the −X-axis, the resultant force of Coriolis force and centrifugal force F1 (F1=−(Fx+f1+f2)) acts on the vibrator, and when it passes on the +X-axis, the resultant force F2 (F2=Fx+f1+f2=−F1) acts on the vibrator. As can be seen from this, Coriolis force and centrifugal force, which are in the same direction, are indistinctive. However, centrifugal force f1 can be considered to be constant if the rotating radius and rotating cycle do not change, and f2 can be considered to be small enough compared with f1. Therefore, centrifugal force can be considered as an offset, and Coriolis force can be detected from changes in force. Move specifically, angular velocity ωz can be measured.

3.2 When the Rotation axis of the Vibrator and the Rotation axis of the Input are not in Agreement While the vibrator is rotating at angular velocity Ω around the Z-axis, assume that angular velocity ωz acts around an axis different from the rotation axis of the vibrator. At first, with this rotation Ω, when the vibrator passes on the −X-axis, centrifugal force −f1 acts in the X-axis direction. With the vibrator rotated 180 degrees, when it passes on the +X-axis, centrifugal force +f1 acts in the X-axis direction. In this state, when angular velocity ωz acts around an axis different from the rotation axis of the vibrator, Coriolis force −Fx and centrifugal force −f2 in the X-axis direction are newly produced with ωz. With the vibrator rotated 180 degrees, Coriolis force +Fx and centrifugal force −f2 in the X-axis direction are newly produced with angular velocity ωz. This state is shown in Fig. 4.

When the vibrator passes on the −X-axis, the resultant force of Coriolis force and centrifugal force F1 (F1=−(Fx+f1+f2)) acts on the vibrator, and when it passes on the +X-axis, the resultant force F2 (F2=Fx+f1−f2) acts on the vibrator. From this relationship, centrifugal force f2 by angular velocity ωz can be cancelled by detecting the difference between F1 and F2, while centrifugal force f1 cannot be cancelled due to the rotation Ω of the vibrator.

In any case, where the angular velocity ωz of the same rotation as the rotation axis of the vibrator is detected, since centrifugal force by the rotation axis of the vibrator acts as a disturbance with respect to Coriolis force, great care should be taken in detecting the angular velocity.

4. Construction of the 3-axis Angular Velocity Sensor

For the piezoelectric effect, the cross-sectional view of the 3-axis angular velocity sensor is shown in Fig. 5. The piezoelectric element substrate is bonded to the top face of the diaphragm made of elinvar, and the vibrator is joined to the back.

The node point of the diaphragm is supported, and fixed to the package. The surface of the piezoelectric ceramic substrate is shown in Fig. 6.

Nine divided electrodes are formed on the surface. Coriolis force is detected by the four sector electrodes (x+, x−, y+, y−) placed at the center. Coriolis force in the X-axis direction is detected from the difference in charge produced between the two electrodes (x+, x−) placed on the X-axis, and Coriolis force in the Y-axis direction is detected from the difference in charge produced between the two electrodes (y+, y−) placed on the Y-axis also. The four electrodes (X+, X−, Y+, Y−) placed outside the detecting electrodes are used for bringing the vibrator into rotational motion, and the vibrator makes rotational motion on the X-Y plane when AC signals with 90 degrees phase shift are applied. Ring electrode Z placed outermost is to monitor the motion in the Z-axis direction, which is used for synchronous detection. The placement of the nine electrodes shown here is determined by FEM analysis. Especially, the positions

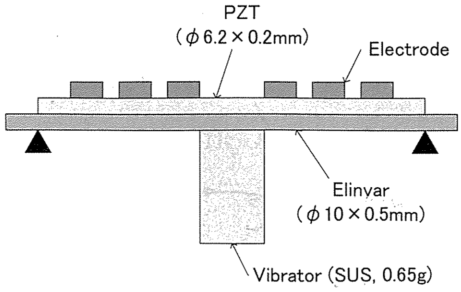


Fig. 5. Cross-section of the 3-axis angular velocity sensor

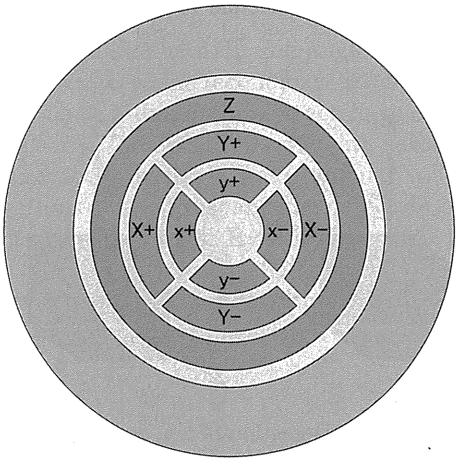


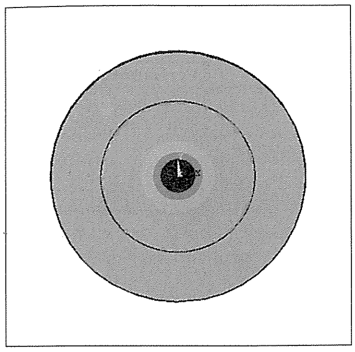
Fig. 6. Surface of the piezoelectric ceramic substrate

of electrodes (x+, x−, y+, y−) detecting Coriolis force are important, which must be placed in the stress concentration area. The results of FEM analysis of stress and displacement in this construction are shown in Fig. 7 and Fig. 8. From these results, it can be seen that stress concentrates around the vibrator joining part. If the Coriolis force detecting electrodes (x+, x−, y+, y−) are placed in this area, Coriolis force can efficiently be detected. It is efficient to bring the vibrator into rotational motion by the surrounding four electrodes (X+, X−, Y+, Y−).

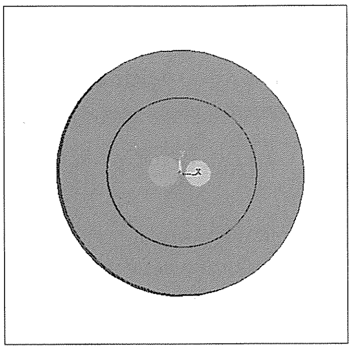
The impedance characteristics when the vibrator of the actually developed 3-axis angular velocity sensor is vibrated in the X-axis direction, Y-axis direction and Z-axis direction are shown in Fig. 9.

5. Detection Circuit of the 3-axis Angular Velocity Sensor

Since the vibrator of the 3-axis angular velocity sensor makes rotational motion as shown in Fig. 1, the velocity components are constant. In this research, the vibrator was brought into rotational motion on the X-Z plane in consideration of the detection sensitivity and noise resistance. When passing on the X-axis, it has a velocity component in the Z-axis direction, and when passing on the Z-axis, it has a velocity component in the X-axis direction. If Coriolis force is measured in the X-axis direction and Y-axis direction the instant when it passes on the X-axis (velocity component Vz), angular velocity ωx and angular velocity ωy can be detected.

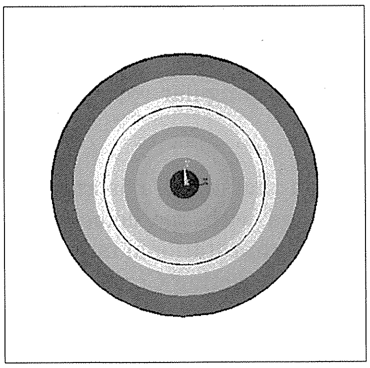


(a) Stress distribution of Z

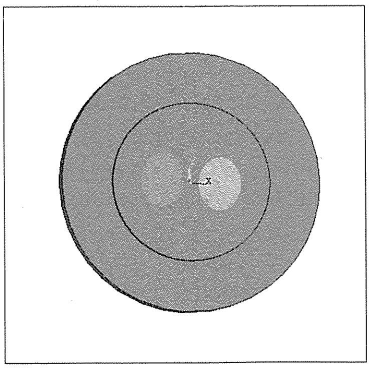


(b) Stress distribution of X

Fig. 7. FEM analysis of stress



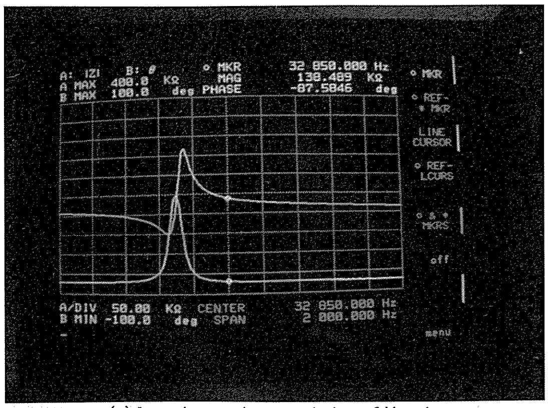
(a) Displacement distribution of Z



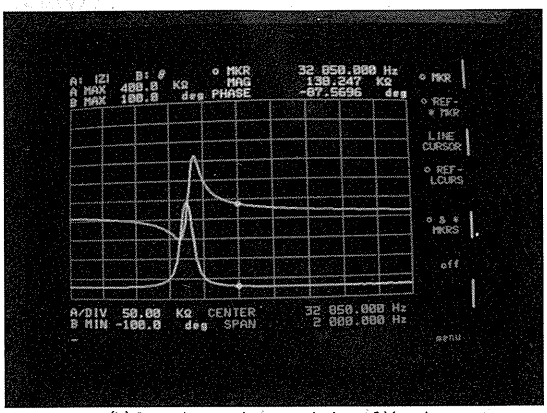
(b) Displacement distribution of X

Fig. 8. FEM analysis of displacement

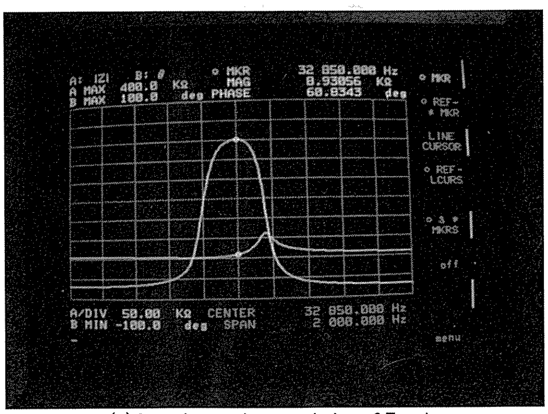
Furthermore, if Coriolis force is measured in the Y-axis direction the instant when it passes on the Z-axis (velocity component Vx), angular velocity ωz can be detected. Rotational motion on the X-Z plane is made by applying signals with a phase difference of 0°, 90°, 180°, 270°



(a) Impedance characteristics of X-axis



(b) Impedance characteristics of Y-axis



(c) Impedance characteristics of Z-axis

Fig. 9. Impedance characteristics of the 3-axis angular velocity sensor

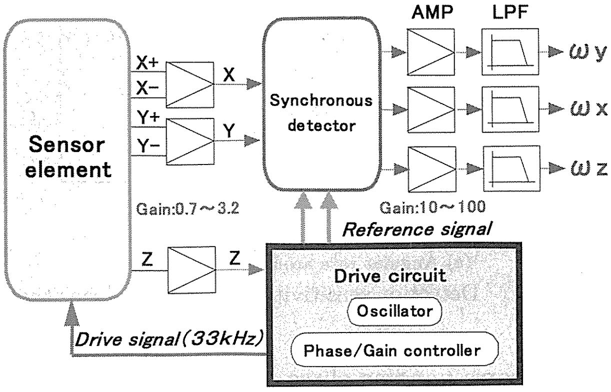
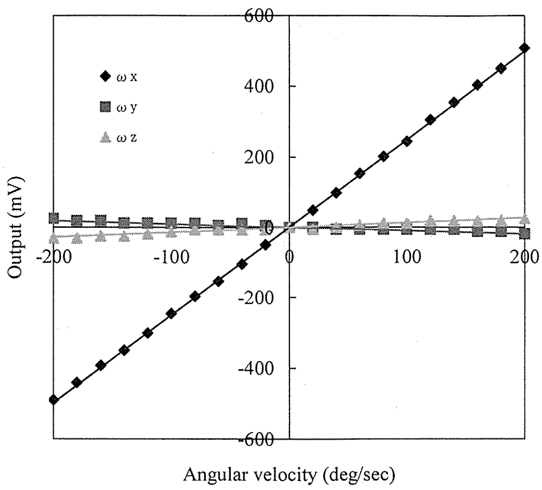
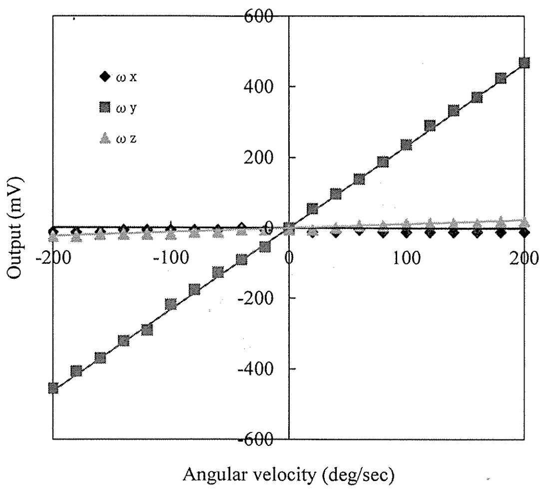


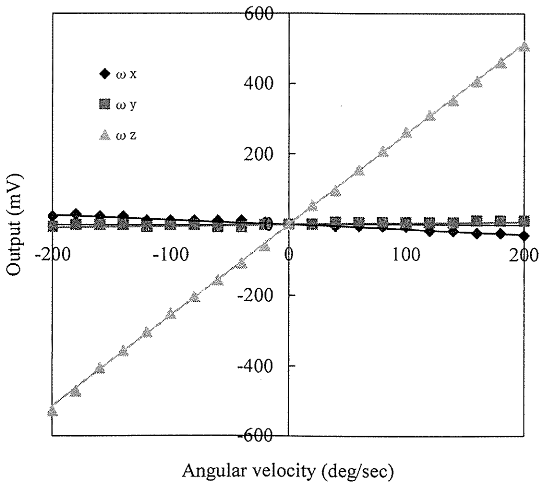
Fig. 10. Circuit block diagram of 3-axis angular velocity sensor



(a) Angular rate around Z-axis (ωx)



(b) Angular rate around Y-axis (ωy)



(c) Angular rate around Z-axis (ωz)

Fig. 11. Detection sensitivity and cross-axis sensitivity

from the corresponding phase of the electrodes (X+ and X−) on the X-axis alternately, and Coriolis force in the X-axis direction and Y-axis direction is detected from the charge produced between the central four detecting electrodes (x+, x−, y+, y−).

Table 1. Performance of 3-axis angular velocity sensor

Items	Performance
Detection axis	3-axis(X, Y, Z)
Sensitivity	2.5mV/deg/sec
Cross-axis sensitivity	5%
Non-linearity	3%
Response frequency	DC-50Hz

The circuit block diagram used for detecting 3-axis angular velocity is shown in Fig. 10.

Synchronous detection of the signals from the detecting electrodes (x+, x−, y+, y−) with the drive signal (33kHz) of the vibrator can be seen.

6. Performance of the 3-axis Angular Velocity Sensor

The principal axis sensitivity and cross-axis sensitivity of the 3-axis angular velocity sensor we have developed recently are shown in Fig. 11. It can be seen that the cross-axis sensitivity is 5% or less on each axis. Performance is shown in Table 1. Compared with the piezoelectric ceramic 1-axis angular velocity sensor that is commercially available at present, we have found that the 3-axis angular velocity sensor can achieve performance of the same level in the cross-axis sensitivity, nonlinearity et al. and it may have the performance which is equivalent to three 1-axis angular velocity sensors.

7. Conclusion

This report has shown that the 3-axis angular velocity sensor can be detected with one detecting element by bringing the vibrator into rotational motion within a 2-dimensional plane, and detecting Coriolis force in the directions of two axes. In this research, the vibrator was brought into rotational motion and Coriolis force was detected by using the piezoelectric effect of the piezoelectric element, but the vibrator may be brought into rotational motion by Coulomb force and Coriolis force being detected by electrostatic capacitance.

In this case, it is considered that compact and highly reliable 3-axis angular velocity sensors can be realized with use of micro-machining technology. We think that research in this field will advance in synchronicity with market trends in the future.

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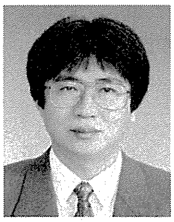

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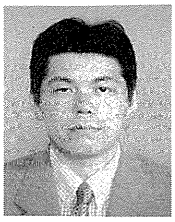

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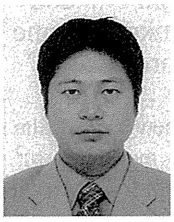

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