Vibrating structure piezoelectric hollow cylinder gyroscope

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This paper presents the development of piezoelectric vibrating structure gyroscope. The vibrating structure used here is made of piezoelectric PZT-5J and cylindrical in shape. It has eight equally spaced positive electrodes on the outer side and one common negative electrode on the inner side. Two of the positive electrodes are used for excitation of the structure and two for detection. The excitation of structure is done at its resonance frequency providing maximum sensitivity. The performance of the developed piezoelectric gyroscope is tested with a microprocessor controlled turntable. Signal conditioning with automatic gain control (AGC) and results, for clockwise and anti-clockwise rotations for different rotation speeds, are discussed in the paper.

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Vibrating structure gyroscopes are state-of-art devices, based on the Coriolis effect which arises in a rotating frame of reference, and use Coriolis acceleration effect to sense rotation. This is accomplished by establishing an oscillatory motion orthogonal to the i/p axis, in a sensing element within the gyroscope. When sensor is rotated about its i/p axis, vibrating element experiences Coriolis force in a direction tangential to the rotation (orthogonal to vibratory and rotating axis). Vibrating structure gyro have several advantages over conventional spinning wheel gyroscopes. They have low power requirements, short startup time and very low inherent noise and also, troublesome bearings are totally eliminated. These gyroscopes are autonomous and do not rely on any external aids, and are well suited for integrated navigation, guidance and control of host vehicle. Applications requiring lower performance have generally been targeted by vibratory gyroscope developers. More recently, potential markets in the automotive and consumer goods industries have attracted significant attention for purely commercial applications. As the technology develops and vibratory gyroscopes become smaller, cheaper with higher performance, many more applications will become possible.

Theoretical Background
Piezoelectric gyroscope makes use of two vibration modes of a piezoelectric body, in which material particles move in perpendicular directions, so that the two modes are coupled by Coriolis force on rotation. The resonant frequencies of these two modes are very close to each other for the gyroscope to work at resonance for maximum sensitivity. Two modes satisfying these criteria are fundamental to piezoelectric gyroscopes and are called a pair of gyroscopic modes (Fig. 1), examples include flexural vibrations in two perpendicular directions of beams, thickness shear in two perpendicular directions of plates, radial and torsional vibrations of circular cylindrical shells, coupled radial and azimuthal vibrations of circular plates and cylindrical shells. To measure angular velocity, the particle is made to vibrate with constant amplitude along the axis OX (say). This motion is referred to as primary motion (or driven motion). When the gyroscope rotates, particles experience a Coriolis inertia force.

![Fig. 1—Radial displacements of primary and secondary (gyroscopic) modes of operation](image)
This force has magnitude proportional to angular rate ($\Omega$) and direction along the axis OY. This motion is referred to as secondary motion (sensing motion). Measurement of its amplitude will provide an estimate of the angular velocity $\Omega$. The sensitivity of vibrating gyroscope can be determined by

$$S = \frac{Y_0}{\Omega} = \frac{2\omega_x X_0}{\sqrt{\omega_y^2 (1-r^2)^2 + (r/Q)^2}}$$

where $Y_0$ is magnitude of sensing motion, $\Omega$ is angular rate, $\omega_x$ is excitation frequency in OX axis, $\omega_y$ is resonant frequency of sensing motion in OY axis. It can be seen from this equation, when $r = (\omega_x / \omega_y) = 1$, sensitivity reaches its maximum value, i.e., $S = 2Q X_0 / \omega_y$. Here, $Q$ is mechanical quality factor for the sensing motion. High quality factor implies that the energy exchange with the surroundings is small, implying that external vibrations will only slightly affect the device vibrations.

**Experimental Procedure**

**Piezoelectric cylinder gyroscope development**

The most commonly used piezoelectric material is lead zirconate titanate (PZT). The PZT exhibits most of the characteristics of ceramics and both the direct and converse piezoelectric effects. Both excitation and detection have been done through the piezoelectric effect. In the design of a cylinder gyroscope using a piezoelectric material, it is important to choose the material and the cylinder axis so that the material constitutive relationships are invariant with respect to rotation of the cylinder axis. If this is done, then a thin cylinder of this material would behave as isotropic. This requirement is met only if the cylinder is manufactured from radially polarized PZT material. In the analysis of PZT sensors, PZT material is assumed to be transversely isotropic\(^{10}\), for piezoelectric properties, in the plane normal to the poling direction. The theory of piezoelectric gyroscopes has been reported elsewhere\(^{11-14}\). Loveday and Rogers\(^{14}\) have done detailed theoretical analysis of piezoelectric cylinder gyroscope.

The cylinder is assumed to be perfectly symmetric about the axis and rigidly fixed at its base to the supporting casing. One end of the piezoelectric cylinder is bonded to an aluminum disc leaving one end free to vibrate. The aluminum disc is fixed onto the top of stepper motor shaft with an acrylic rod attachment which is extended further and mounted on to this rod are four slip ring connectors, as shown in Fig. 2, each having carbon brush assembly. Thus, four slip rings are used, viz., two for detection, one for excitation and one for negative electrode connection. Enamelled insulated copper wires are used to establish connection between the electrodes on piezoelectric cylinder and the slip rings. Piezoelectric cylinder used is made from PZT-5J and dimensions 33 mm OD, 28 mm ID, 2.5 mm thickness, inside fully electroded and poled negatively, outside eight electrodes separated by 2 mm margin, poled positively. The piezoelectric ceramic cylinder is excited at its natural frequency of 191 kHz through function generator 8038C. Out of eight electrodes available only four are used. Two diagonally opposite positive electrodes are short together and a single wire is taken out and used for excitation of the ceramic cylinder. Two more electrodes orthogonal to the excitation electrodes are selected and copper wires are connected to them, which are then connected to respective slip rings. The complete block diagram of piezoelectric cylinder gyroscope is shown in Fig. 2.

The output of the detector electrodes is connected to current to voltage converter which is further connected to buffer amplifier. A feedback is given to excitation circuit comprising 8038C function generator through automatic gain control circuit. This circuit helps to control the amplitude and frequency variations to minimum, thus giving a stable output.

Fig. 2—Experimental set-up block diagram of piezoelectric cylinder gyroscope, turn table test set-up, cylinder fixing arrangement, excitation and detection circuit
Operation

To test the performance of developed gyroscope a microprocessor based turntable has been used to provide fixed rotation to the unit mounted on the shaft of stepper motor as shown in Fig. 2. The 8085 microprocessor has been interfaced with the stepper motor driver card. The turntable is microprocessor based and has been calibrated for different speeds to suit rotation of the gyroscope using microprocessor 8085. The microprocessor program corresponding to the speed is changed serially and different speeds are being measured with the help of a tachometer.

A voltage applied to a pair of electrodes produces an axial electric field in that region of the cylinder, which is defined by the shape of the excitation electrodes. If periodic, this field drives the piezoelectric ceramic cylinder into resonant vibration due to piezoelectric action and can excite a combined radial and torsional mode of vibration in which the radial displacement has the form as shown in Fig. 1. The nodal lines of this mode will occur at $\pm 45^\circ$ with respect to axis OX.

Signal conditioning

The resonant frequency of the cylinder gyroscope has been determined with the help of an oscillator. At the natural frequency, the cylinder will have maximum vibrating amplitude and hence maximum strain on the piezoelectric cylinder and as a result of inverse piezoelectric effect, the output will be maximum. This cylinder is excited with 20 V ac signal, generated from the Systronics function generator. The output from the detection electrode is taken through the current to voltage converter and displayed on the oscilloscope. As the input frequency to the cylinder from the function generator is varied manually, the output changes. This output will reach a maximum value at the resonant frequency. The resonant frequency of the vibrating structure (cylinder) has been found to be 191 kHz. Hence, this cylinder is excited with 3 V, 191 kHz ac signal from 8038C function generator for gyroscopic operation. When the cylinder is rotated through the stepper motor at excited condition, the secondary mode of vibration is generated as a result of the Coriolis force. Using the inverse piezoelectric effect, the modal response produced by this excitation can be measured directly by taking the current produced by one of the detection electrodes through a high input impedance current to voltage converter. This circuit takes the advantage of the versatility of the operational amplifier LM 741. A second measurement electrode is provided by connecting the terminal to a second high input impedance current to voltage converter A2. Since these electrodes are centered precisely on the 45° nodal lines of the foregoing mode, they will register no output current as a result of the oscillator vibration. If the cylinder is now rotated about OZ, Coriolis inertia forces will excite a secondary motion. This motion will cause an output to be generated by A1 and A2. The voltages are applied to a unity gain differential amplifier as shown in Fig. 3. The value of the differential voltage is taken as the measure of the applied rate of turn.

Automatic gain control (AGC)

The primary ideal function of the circuit is to maintain a constant signal level at the output, regardless of variations at the input. The input signal is amplified by a variable gain amplifier (VGA), whose gain is controlled by an external signal VC. The output from the VGA can be further amplified by a second stage to generate an adequate level of VO as shown in Fig. 4. Some of the output signal’s parameters, such as amplitude, carrier frequency, index of modulation or frequency, are sensed by the detector; any undesired component is filtered out and the remaining signal is compared with a reference signal. The result of the comparison is used to generate the control voltage (VC) and adjust the gain of the VGA. For low input signals, the AGC is disabled and the output is a linear function of the input. When the output reaches a threshold value (V1), the AGC becomes operative and maintains a constant output level until it reaches a second threshold value (V2). At this point, the AGC becomes

![Fig. 3—Schematic showing differential amplifier circuit with unity gain after current to voltage converter](image-url)
inoperative again. This is usually done in order to prevent unstability problems at high levels of gain.

The AGC circuit\textsuperscript{15} used is shown in Fig. 5. The circuit composed in IC (2/2) is the full-wave rectification circuit. When the output voltage of the oscillator is positive, the signal spreads through the negative input terminal of IC (2/2) through D2. At the positive input terminal, it is prevented by D3 and the signal doesn't spread. IC (2/2) does the inverting gain amplification. The output of IC (2/2) becomes the negative voltage. Next, when the output voltage of the oscillator is negative, the signal spreads through the positive input terminal of IC (2/2) through D3. At the negative input terminal, it is prevented by D2 and the signal doesn't spread. Now IC (2/2) does the non inverting gain amplification and so the output of IC (2/2) becomes the negative voltage. In this way, output by IC (2/2) is voltage which is always negative. As the output of IC (2/2) is the ripple current, there is a smoothing in R7 and C4 through D1 and it makes the total direct current. The d.c. voltage by the full-wave rectification circuit changes with the change of the output voltage of IC (1/2), and is added to the gate of TR1 (FET) through R6. The negative voltage which is gained by the gate of TR1 becomes high when the output signal of IC (1/2) becomes high. Then, the resistance value between the drain and the source of TR1, too, becomes high. The mu factor of IC (1/2) falls when the resistance value of R3 and TR1, which is stored in series, becomes high. The output of IC (1/2) is restrained by it. R5 and C3 improve the frequency characteristic of TR1. It makes the distortion of the oscillation signal by TR1, small. By above operation, the oscillation of IC (1/2) becomes stable. This operation is automatic gain control.

Output of AGC is given to the excitation electrodes so as to control the amplitude variation produced in the output wave due to ripple or any other noise. Final output signal is taken from differential amplifier in buffer configuration, but is in terms of voltages which can be measured through multimeter. The output can be obtained, directly in terms of angular rate, by giving above voltage output to an ADC card interfaced with the computer.

**Results and Discussion**

Figs 6 and 7 show the variation in the output voltage with rotation for a set of observations for the developed piezoelectric gyroscope for clockwise and counter clockwise rotations respectively, at resonant frequency (191 kHz). However, a large number of observations have been taken for different rotations both clockwise and counter clockwise. It is observed from the figures that the output voltage increases for clockwise rotation and decreases for the counterclockwise rotation. Hence, it enables the detection of direction of rotation. For clockwise rotation, the increased voltage remains constant until it is rotated counter clockwise to decrease it to the same reference voltage. The results obtained are in accordance with the operating principle of a gyroscope.

The results discussed here use gain of the current to voltage converter at 10 with a feedback resistor of 10 kΩ. The differential amplifier is used in the buffer amplifier configuration. The current to voltage converter along with buffer amplifier are acting as
instrumentation amplifier. This differential amplifier passes the differential voltage from the two current to voltage converters and gives signal to an automatic gain control, the extent of control of which is controlled through a voltage divider circuit. FET IR 9630 is employed in the AGC circuit. The LM 741 operational amplifier has been used for both the current to voltage converter and the differential amplifier circuits. The output ac voltage thus obtained from the differential amplifier is displayed using a six and a half digit multimeter (Keithley 2000) and observed simultaneously on a digital storage oscilloscope and the variation in o/p voltage shows the effect of rotation as presented in Figs 6 and 7.

From the results and the corresponding graphs, it can be seen that the gyroscope operates linearly up to a rotation rate of approximately 200 °/s, where after the results are non-linear. Hence, this gyroscope can be used up to a maximum rotational speed of 200 °/s. For commercial and defence applications, the maximum range for rotation required is 50 °/s. It can be seen that the gyroscope design is very much applicable for the commercial applications, as well as, for defence applications from the measurement range point of view. In the linear range, the sensitivity of the piezoelectric ceramic cylinder gyroscope is obtained as 0.3 mV/ °/s.

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References
15. Issac M G, AGC circuit theory and design, University of Toronto, 2001 (personal communication).

Fig. 6—Effect of rotation on o/p voltage for piezoelectric cylinder gyroscope at resonance frequency (191 kHz) for clockwise rotation

Fig. 7—Effect of rotation on o/p voltage for piezoelectric cylinder gyroscope at resonance frequency (191 kHz) for counter clockwise rotation