Vibrating single crystal piezoelectric disc gyroscope

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This paper deals with a single crystal piezoelectric disc gyro sensor. The principle of basic operation and the practical structure of the disc vibrating gyro has been described along with the experimental results for a prototype of the gyro sensor. The results obtained show that the proposed disc resonator operates as a gyro sensor, having sensitivity of about 0.9 mV/°s, and behaves almost linear in the range of up to 180 °s.

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1 Introduction

Recently, vibratory gyroscopes are being used in many industrial applications\(^{1,5}\) i.e. image stabilizing systems of camcorders, direction sensors of car navigation systems, etc., however, early efforts were motivated by military applications\(^{8,9}\) where space had been the main restriction, including guidance and stabilization of missiles, stabilization of gun, camera and antenna platforms, smart munitions including gun-fired munitions and GPS augmented navigation, stabilization and navigation of underwater vehicle. These gyroscopes offer important advantages over the traditional gyroscopes.

Vibrating gyroscopes work on the principle of the Coriolis acceleration. This acceleration is experienced by a particle undergoing linear motion, in a frame of reference rotating about an axis perpendicular to that of the linear motion. The resulting acceleration is directly proportional to the rate of turn, occurs in the third axis, which is perpendicular to the plane containing the other two axes. In these sensors, vibration motion is coupled from a primary vibrating mode into a secondary mode, when the sensor experiences angular rate. In recent years, several different types of vibratory gyroscopes have been proposed\(^{6,9}\) and developed. These can be subdivided into three groups as follows: (i) simple oscillator i.e. mass on a string, beam\(^6\), (ii) balanced oscillators i.e. tuning forks\(^9\) and (iii) shell resonators i.e. ring\(^9\), cylinder\(^9\), disc\(^9\). By correct design of a shell resonator, it is possible to overcome problems associated with resonator mount sensitivity, experienced by simple oscillators and balanced oscillators, and thus improve bias performance and reduce sensitivity to shock and vibration. Also, the layout of the sensor is very important, as it decides the rotation axis of the equipment. Almost, all vibrating gyro sensors, which are being used practically and are being studied at present, are long in the same direction as the detection axis. Hence, these gyroscopes cannot be used in the case of thinly packed equipment and inadequate space in the direction of detection axis. Therefore, a flat structured gyro sensor for detection axis, is in demand.

The purpose of this study is to develop a flatly equipped gyro sensor. Besides this, vibrating disc structure has certain added advantages over other types of vibratory gyroscopes—(a) The inherent symmetry of the structure makes it less sensitive to spurious vibrations. (b) As two identical flexural modes of the structure, with equal resonant frequencies, are used to sense the rotation, the sensitivity of the sensor is amplified by the quality factor of the structure, resulting in higher sensitivity. (c) The vibrating disc is less sensitive to temperature, since both the vibration modes are equally affected by the temperature.

The theory of piezoelectric gyroscopes is well established and discussed elsewhere\(^7,8,13\) and, in particular by Tamura et al.\(^7\) and Burdess and Wren\(^13\) deals with disc gyroscopes. The developed gyro is made of thin piezoelectric disc, axially polarized PZT,
on which, are deposited drive and pickoff electrodes to give the monolithic arrangement. This is achieved by making the disc out of piezoelectric material and providing the drive and detection mechanism via simple electrodes deposited on the surface of the disc. Disc gyroscopes are based on in-plane vibration of thin piezoelectric disc, which is rotated about its polar axis.

2 Experimental Details

Figure 1 shows the basic design of the disc gyroscope sensor. The disc is made of PZT (SP – 5H trade name of manufacturer) material and has a diameter of 10 mm and thickness 1 mm. Eight equispaced identical positive electrodes numbered 1 to 8 are deposited on the upper surface of the disc, covering outer diameter of 5 mm as shown in the figure. A single negative electrode covers the whole of the lower surface of the disc. The piezoelectric disc of this required electrode design has been manufactured by M/s Sparkler Ceramics, Pune, as per the given drawing and specifications. The centerline of electrode 1 is defined by the axis OX. Electrodes 1 and 5 are paired to drive the disc at resonance. A sinusoidal voltage, at the mechanical resonance frequency, is applied to the excitation electrodes (1 and 5).

The experimental setup of the piezoelectric disc gyrooscope is shown in Fig. 2. The disc is rigidly fixed at its inner radius to a turntable, the stepper motor stem and is excited through a Systronics function generator. The output of this disc is taken through a bunch of wires containing nine flexible wires. Eight wires are connected to eight equispaced identical positive electrodes 1 to 8, and the ninth wire is connected to the negative electrode. The disc output is fed to the signal conditioner circuit and the output is displayed on the Keithley 6 1/2 digital multimeter and on digital storage oscilloscope. The stepper motor is operated through a microprocessor based controlled driver card. The 8085 microprocessor has been interfaced with the stepper motor driver card. The stepper motor used is 6/12V permanent magnet, 2 phase, 1.8° ± 5 % full step, 200 steps/rev, 0.5 A/phase, holding torque is 2 kg cm⁻¹ with single phase energized, 2.8 kg cm⁻² with both phases energized, rotor inertia 0.1 kg cm⁻².

3 Piezoelectric Gyro Operation

Since the disc is thin, a voltage applied to terminals 1 and 5 will produce an axial electric field in that region of the disc, which is defined by the shape of the electrodes 1 and 5. This periodic field can be used to drive the disc into resonant vibration due to piezoelectric action and can excite a combined radial and torsional mode of vibration with radial displacement. The nodal lines of this mode will occur at ±45° with respect to axis OX. A large o/p signal is obtained if large drive amplitude is used, which is obtained by utilizing one of the drive resonance frequencies. The o/p signal can be further increased by letting the resonance frequencies of the sense vibration to be same as the drive frequency. The resonant frequency of the disc has been determined experimentally. At the natural frequency, the disc will have maximum vibrating amplitude and hence maximum strain on the piezoelectric disc and as a result of inverse piezoelectric effect, output will be maximum. This disc is excited with 20-volt ac signal, generated from the Systronics function generator. The output from electrode 3 is taken through the current to voltage converter and displayed on the oscilloscope. Now, as the input frequency to the disc from the function generator is varied manually, the output keeps changing. This output will touch a maximum value at the resonant frequency of the disc which has been measured and found to be 148 kHz. The disc is excited with 148 kHz ac signal of 20 V for gyroscopic operation.

When this disc 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 electrode 4 through a high input impedance current to voltage converter as shown in Fig. 2. A second measurement electrode 8 is provided by connecting the terminal to a second high input impedance current to voltage converter. 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 disc is now rotated about OZ, Coriolis inertia forces will excite a secondary motion. This motion will cause an output to be generated by A_1 and A_2. The voltages are applied to a high gain differential amplifier as shown in Fig. 2. The value of the differential voltage is taken as the measure of the applied rate of turn.

Thus, the primary and secondary modes of the piezoelectric disc can be excited electrically by pairs of surface electrodes. A rate of turn produces a dynamic coupling between these modes of the piezoelectric disc and thereby, because of piezoelectric action, causes a voltage to be generated at another electrode pair, which can be taken as a measure of the applied rate of turn.

4 Results and Analysis

The overall performance of the gyroscope and electronics has been tested using programmable stepper motor turntable which has been calibrated for different speeds to suit rotation of the gyroscope. The microprocessor program corresponding to the speed is changed serially and different speeds corresponding to the program are being measured with the help of a tachometer. Under rotation output of the sensor has been measured and it is observed that o/p of gyro sensor consists of ac and dc signal which changes with rotation of turntable. The output waveforms of the ac and dc components of signal are shown, respectively, in Fig. 3 (without rotation) and Fig. 4 (after rotation), and in Fig. 5 (without rotation) and Fig. 6 (after rotation). The results for different speeds of counter clockwise rotation of the gyroscope are tabulated in Table 1 for ac component of signal and in Table 2 for dc. The variation of output (average of three readings for ac and dc component) with rotation speed is shown in Fig. 7 and Fig. 8. From the results it is observed that for counter clockwise rotation, the increased voltage remains unchanged until it is rotated clockwise to
Fig. 3—Output ac signal waveform without rotation

Fig. 4—Output ac signal waveform after counter clockwise rotation

Fig. 5—Output signal dc waveform without rotation

Fig. 6—Output dc signal waveform after counter clockwise rotation
Fig. 7—Variation of output (ac signal) with rotation speed

![Graph of Fig. 7 showing variation of output (ac signal) with rotation speed.]

Fig. 8—Variation of output (dc signal) with rotation speed

![Graph of Fig. 8 showing variation of output (dc signal) with rotation speed.]

Table 1—Output voltage (ac) for gyroscope without and with counter clockwise rotation for different speeds

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<th>Diff</th>
<th>W/O Rtn</th>
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decrease it to the same reference voltage. Hence, the developed gyroscope is able to detect the direction of rotation also. For consecutive rotations in the same direction, the voltage increases or decreases as per the direction.

From the results and the corresponding graphs, it can be seen that the gyroscope operates linearly up to a rotation rate of approximately 180°/s, after which it shows non linear behaviour. In the linear range, the dc output sensitivity of gyroscope is about 0.9 mV/°/s and ac output sensitivity is about 0.06 mV/°/s. For various applications, the maximum range for rotation required is about 50-60°/s and the designed gyroscope, which can be used up to a maximum rotation speed of 180°/s, suits most of the applications.

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References
4 Gates W D, Electronics, 10 (1968) 130.