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Development of Vibrating Disc Piezoelectric Gyroscope

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ABSTRACT

The paper presents an indigenously developed vibrating disc piezoelectric gyroscope, in which both excitation and detection have been done through piezoelectric, using PZT-5H material. The gyroscope has been driven to resonant state by direct piezoelectric effect, using 20 V ac signal at 93 kHz, and the output has been detected by the reverse piezoelectric effect. The performance of this gyroscope has been tested with 3 microprocessor-controlled turntable, and the output of the gyroscope has been found to be linearly proportional to the rotation speed within a range ± 150 °/s. The sensitivity of the gyroscope is about 0.5 mV/°/s, which is comparable to that of other gyroscopes of similar category.

Keywords: Piezoelectric gyroscope, vibrating disc, rotation rate sensor, resonance frequency, Coriolis effect, piezoelectric effect, vibrating gyroscope

1. INTRODUCTION

The vibrating gyroscopes are inertial instruments, based on the Coriolis effect, used to measure angular rotation rate. Gyroscopes, in general, can be classified into three categories, based on their performances, viz., (i) inertial grade, (ii) tactical grade, and (iii) rate grade. Optical gyroscopes are considered to be the most accurate; out of which ring laser gyros have demonstrated inertial-grade performance, while fibreoptic gyros are mainly used for tactical-grade applications. However, optical gyroscopes are too expensive and bulky for many applications. Solid-state nature of the vibrating gyroscopes makes various unique features possible. Also, there are no motors or bearings. These sensors can be designed to be extremely rugged and have long service life without the need for maintenance, have very short startup time, low-power consumption, small size, and low cost, and have also achieved inertial-grade performance.

By simply placing a piezoelectric gyroscope in a desired location or position, on an object, the angular velocity of the object, unaffected by the mounting position, can be accurately detected. Early research on piezoelectric gyroscope was motivated by military applications for designing hi-tech sophisticated weapons, with space as the main constraint. Recently, the piezoelectric gyroscope is being utilised in various fields[1-2] and an increasingly strong demand has prompted research interest for a constantly decreased size, improved accuracy, and reduced cost. With the spread of navigation systems and the camera-shake detection function in video movies (VCR integrated with a camera), the piezoelectric gyroscope has attracted wide attention[3]. As the technology advances, vibratory gyroscopes[4,5] become smaller, cheaper, and perform better, and many more applications will become possible.

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The major difference between the conventional mechanical gyroscope and the vibrating gyroscope is that instead of spinning wheel used in the former, the latter uses momentum of a vibrating elastic body. In a vibratory gyroscope, an elastic body or a resonator is forced to vibrate in a flexible mode by attaching a piezoelectric material. When the resonator is rotated about the sensitive axis, the vibration pattern changes and this change is used as a measure of the applied rotation rate. These angular rate sensors make the use of two vibrating modes: (i) primary mode arises due to the excitation and (ii) secondary one arises due to the Coriolis force in a rotating frame of reference. In these two vibrating modes, the material particles move in perpendicular directions, so that the Coriolis force couples the two vibrating modes. Furthermore, the resonant frequencies of these two vibrating modes are very close to each other, for the gyroscope to work at resonance for maximum sensitivity. These two vibrating modes are called a pair of gyroscopic modes. When a piezoelectric gyroscope is excited into a vibration in the primary mode by an applied alternating voltage and attached to a rotating body, the Coriolis force couples energy from the primary mode of a vibration into a secondary mode of a vibration and excites this secondary mode of a vibration, as shown in the Fig. 1. This transfer of energy provides a measure of the applied rotation rate. In this piezoelectric gyroscope, the piezoelectric effect is used both to excite a reference vibration and to detect a vibration caused by the Coriolis force. The amplitude of the secondary mode of vibration is directly proportional to the applied angular rate.

The resonators can be of various geometric structures depending upon the designs[5,10] and may be divided into two classes on the basis of modes of a vibration used during the operation of the gyroscope. In the first class of resonators, the Coriolis coupling between the two dissimilar vibrating modes of different natural frequencies is measured. The resonators forming the second class have two orthogonal vibrating modes, having the same shape and identical natural frequencies, in the absence of imperfections.

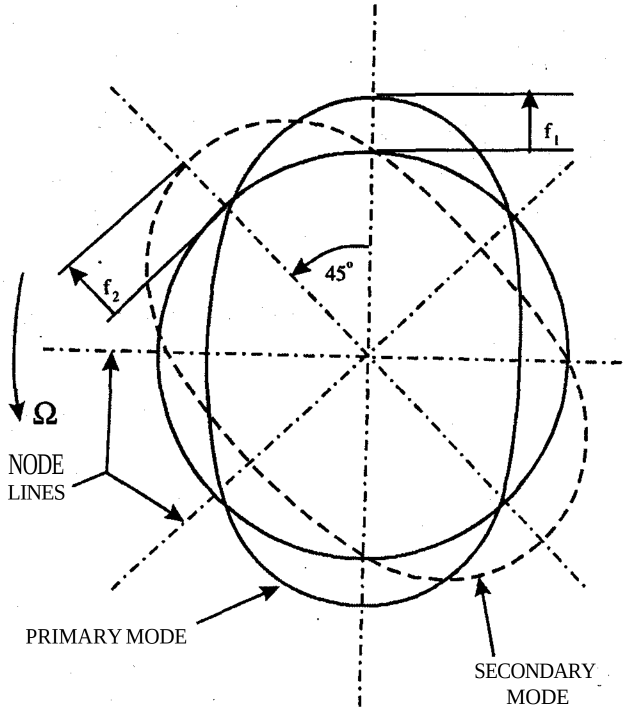

Figure 1. Primary and secondary modes of a vibrating disc piezoelectric gyroscope.

2. DEVELOPMENT OF PIEZOELECTRIC DISC GYROSCOPE

The design and development of a piezoelectric disc gyroscope has been undertaken, as vibrating disc structure has certain advantages over the other types of vibratory gyroscopes. These are:

(a) The inherent symmetry of the structure makes it less sensitive to spurious vibrations.

(b) As the 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 the higher sensitivity.

(c) The vibrating disc is less sensitive to temperature, since both the vibration modes are affected equally by the temperature.

(d) The electronic balancing of the structure is possible. Any frequency mismatch, due to mass or stiffness, can be electronically compensated for using the balancing electrodes located around the structure.

2.1 Construction

The piezoelectric disc gyroscope has been made using axially polarised PZT-5H piezoelectric disc. A metal disc of diameter 30 mm and thickness 0.5 mm has been used for the purpose. The piezoelectric disc is marked and cut carefully into the eight symmetric divisions. The negative electrodes of all these cut piezoelectric pieces are pasted onto the metallic disc, using silver adhesive to make the joints electrically conductive. The positive electrodes of all these cut piezoelectric pieces are now on the upper surface of the disc. This is equivalent to a piezoelectric disc having the eight equispaced electrodes on the upper surface, numbered 1 to 8, and a single electrode on the lower surface.

2.2 Experimental Setup

The experimental setup of the piezoelectric disc gyroscope is shown in the Fig. 2. The disc is rigidly fixed to a turntable, the stepper motor stem, and excited through a systronics function generator at 93 kHz frequency with 20 V ac signal. The output of this disc is taken through a bunch of nine flexible wires. The eight wires are connected to the eight equispaced identical positive electrodes (numbered 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 6 V4 digit Keithley digital multimeter. The stepper motor is operated through a microprocessor-based controlled driver card.

2.3 Operation

Since the disc is thin, a voltage applied to electrodes 1 and 5 produces an axial electric field in that region of the disc, defined by the shape of those electrodes. This periodic field is used to drive the disc into a resonant vibration due to the piezoelectric action, and can excite a combined radial and torsional mode of a vibration with

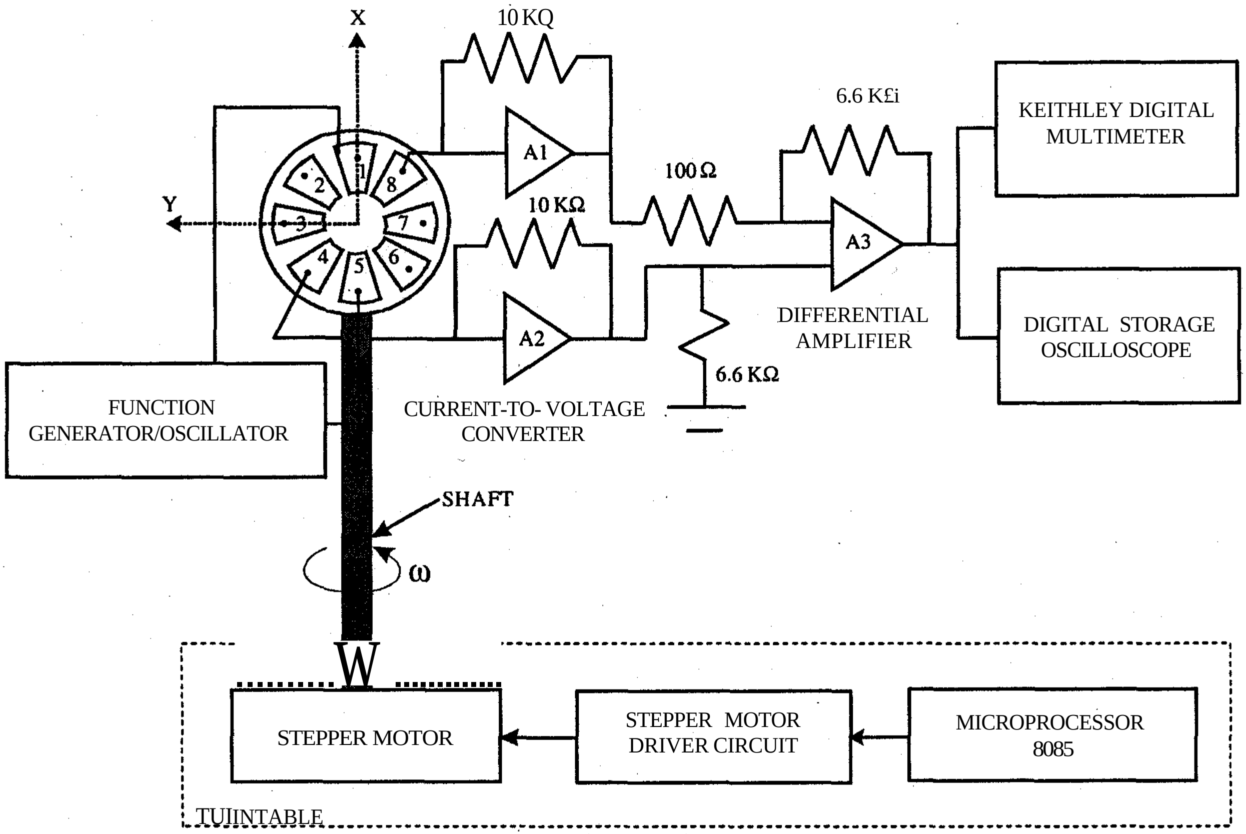

Figure 2. Schematic diagram of a vibrating disc piezoelectric gyroscope along with turntable test setup

radial displacement of the form as shown in the Fig. 1. The nodal lines of this mode will occur at ± 45° wrt axis OX. At natural frequency, the disc will have maximum vibrating amplitude, and hence, there is maximum strain on the piezoelectric disc, and as a result of inverse piezoelectric effect, the output will be maximum. The resonance frequency of the disc has been found experimentally by varying the applied input frequency to the disc from the function generator, and observing the changing output. This output attains a maximum value at the resonant frequency of the disc. The resonant frequency of the disc has been found as 93 kHz. Hence, the disc is excited with 93 kHz, 20 V ac signal for gyroscopic operation.

When this disc is rotated through the stepper motor at an excited condition, the secondary mode of a vibration is generated as a result of the Coriolis force. The modal response produced by this excitation can be measured directly by the inverse piezoelectric effect, taking the current produced by the electrode 4 through a high input impedance current to a voltage convertor, using operational amplifier LM 741(Aj). A second measurement electrode 8 is connected to a second high input impedance current to a voltage convertor A_2 (instead of electrode pair 4 and 8, electrode pair 2 and 6 can also be used). As these electrodes are centered precisely on the 45° nodal lines of the foregoing mode, these will register no output current as a result of the oscillator vibration. If the disc is rotated now, the Coriolis inertia forces will excite a secondary motion as shown by dotted lines in Fig. 1. This motion will cause an output to be generated by A, and A_r The voltages are applied to a high gain differential amplifier. The value of the differential voltage is taken as the measure of the applied rate of turntable.

3. RESULTS & ANALYSIS

The differential output of the vibrating disc piezoelectric gyroscope, without rotation and with rotational speed, for clockwise and counterclockwise motion of the turntable is shown in the Tables 1 and 2, respectively. In these tables, rotational speed for the turntable is presented in rotations per minute (rpm) as well as in degree per second. The turntable is 8085 microprocessor-based and has been calibrated

Table 1. Vibrating disc piezoelectric gyroscope output for clockwise rotation of the stepper motor

Clockwise rotation											
		First reading (mV)			Second reading (mV)			Third reading (mV)			Average change (mV)
rpm	RTN (deg/s)	W/O RTN	AFTR RTN	DIFF	W/O RTN	AFTR RTN	DIFF	W/O RTN	AFTR RTN	DIFF	
6	36	858	870	12	855	865	10	854	868	14	12.00
8	48	744	760	16	740	757	17	740	754	14	15.67
11	66	788	804	16	789	807	18	795	811	16	16.67
16	96	795	820	25	812	840	28	806	838	32	28.33
18	108	834	870	36	836	875	39	800	831	31	35.33
20	120	678	712	34	693	730	37	694	730	36	35.67
22	132	650	690	40	652	693	41	650	691	41	40.67
24	144	670	715	45	665	715	50	664	710	46	47.00
26	156	645	705	60	652	708	56	640	699	59	58.33
28	168	627	715	88	629	710	81	615	691	76	81.67
30	180	591	702	111	595	704	109	580	684	104	108.00
32	192	572	688	116	561	675	114	551	663	112	114.00
34	204	560	673	113	550	650	100	460	574	114	109.00
36	216	556	700	144	438	562	124	430	559	129	132.33
40	240	620	813	193	563	731	168	502	701	199	186.67
43	258	504	607	103	501	598	97	502	606	104	101.33

Table 2. Vibrating disc piezoelectric gyroscope output for counterclockwise rotation of the stepper motor

Counterclockwise rotation											
		First reading (mV)			Second reading (mV)			Third reading (mV)			Average
^	RTN (deg/s)	W/O RTN	AFTR RTN	nTpp	W/O RTN	AFTR RTN	DIFF	W/O RTN	AFTR RTN	nlFF	Change (mV)
6	36	868	857	-11	864	855	-9	865	853	-12	-10.67
8	48	757	744	-13	755	740	-15	754	738	-16	-14.67
11	66	806	787	-19	803	788	-15	808	795	-13	-15.67
16	96	815	792	-23	838	812	-26	835	806	-29	-26.00
18	108	880	845	-35	874	836	-38	888	858	-30	-34.33
20	120	712	678	-34	730	693	-37	730	694	-36	-35.67
22	132	702	661	-41	724	683	-41	715	673	-42	-41.33
24	144	721	675	-46	725	687	-38	708	664	-444	-42.67
26	156	708	650	-58	700	652	-48	705	650	-55	-53.67
28	168	702	627	-75	710	629	-81	691	615	-76	-77.33
30	180	690	591	-99	704	595	-109	684	580	-104	-104.00
32	192	682	575	-107	675	561	-114	663	551	-112	-11.00
34	204	676	560	-116	670	550	-120	574	460	-114	-116.67
36	216	702	556	-146	562	438	-124	559	430	-129	-133.00
40	240	806	620	-186	731	563	-168	701	502	-199	-184.33
43	258	596	504	-92	598	501	-97	606	502	-104	-97.67

for different speeds to suit rotation of the gyroscope having a minimum speed of 6 rpm (36 °/s) and a maximum speed of 65 rpm (390 °/s). The microprocessor program corresponding to the speed is changed serially and different speeds are measured by a tachometer.

In signal conditioning circuit, the gain of the current-to-voltage converter has been maintained at 10 with a feedback resistor of 10 KQ. A 6.6 *KQ.* resistor has been used as the feedback resistor in differential circuit, and 100 *Q* resistor has been used in series with the input supply to get a gain of 66. The LM 741 operational amplifier has been used for both the current-to-voltage converter and the differential amplifier circuits. The output ac voltage available from the differential amplifier is measured by a 6 1/2 digit Keithley digital multimeter and waveform is recorded on a 400 MHz Lecroy storage oscilloscope. A number of experiments were conducted and three sets of results have been presented in Tables 1 and 2. These tables also present average values, which are shown graphically in Figs 3 and 4, for clockwise and counterclockwise rotations of the stepper motor, respectively. It is observed from the graphs that the output voltage increases for the

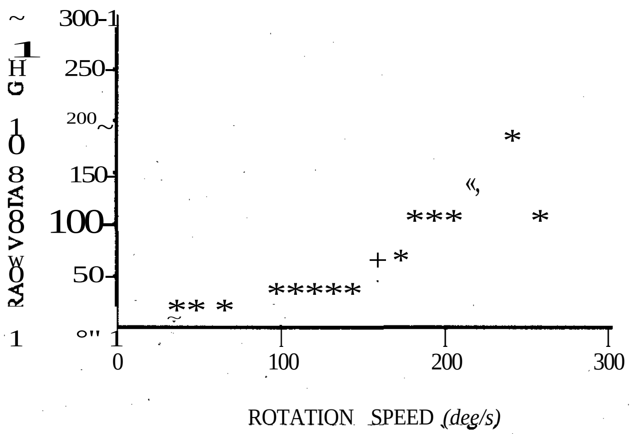

Figure 3. Variation of sensors differential output with rotation speed in degree per second for clockwise rotation of turntable.

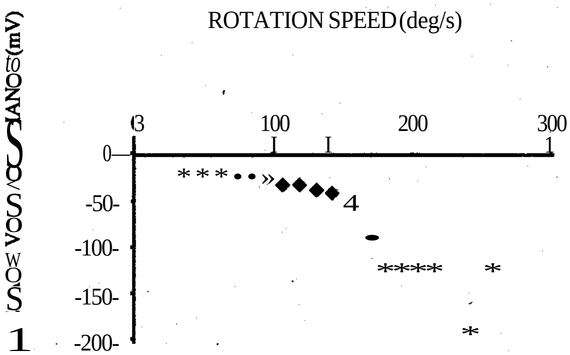

Figure 4. Variation of sensors differential output with rotation speed in degree per second for counterclockwise rotation of turntable.

clockwise rotation of the stepper motor and deceases (increases negatively) for the counterclockwise rotation of the stepper motoV. Hence, the gyroscope is able to detect the direction of a rotation. For the clockwise rotation, the increased voltage remains constant until it is rotated counterclockwise to decrease it to the same reference voltage. For consecutive rotations in the same direction, the voltage increases or decreases as per the direction. These results satisfy the operating principle of a gyroscope.

From the results and the corresponding graphs shown in Figs 3 and 4, it has been observed that the gyroscope operates linearly up to a rotation rate of approximately ±150 °/s, after which the response becomes nonlinear. This gyroscope can be successfully used up to a maximum rotational speed of ± 150 °/s. For most of the commercial applications, the maximum range for rotation required is about 50 °/s, which is much lower than the linear range attained for the developed gyroscope. The sensitivity of the gyroscope obtained is approximately 0.5 mV/°/s, for the linear range, which is comparable to the values reported for other designs and better than the values reported for a disc-type gyroscope[6,9].

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