Defence Science Journal, Vol. 57, No. 1, January 2007, pp. 95-103

REVIEW PAPER

Piezoelectric Gyro Sensor Technology

A.K. Singh

Defence Institute of Advanced Technology, Pune-411 025

ABSTRACT

This paper gives an insight into the piezoelectric gyro sensor technology including the principle of operation, performance-limiting phenomenon, etc. With a brief account of conventional gyro sensor technologies, a detailed discussion on piezoelectric vibrating structure gyro sensor technology has been given. The performance of various forms of vibrating structure piezoelectric gyros, including future trends, has been highlighted.

Keywords: Piezoelectric gyros, sensors, sensor technology, gyro technology, vibratory gyroscopes, smart sensors

1. INTRODUCTION

Gyroscopes are used for numerous defence and commercial applications. These include stabilisation, guidance, and navigation of torpedoes; ballistic missiles and artillery shells; inertial navigation and inertial surveying; autopilot, stabilisation and navigation of underwater vehicle, etc. Recently, automotive and consumer goods industries have shown significant attention towards purely commercial applications which include automobile accident-history recorder and stabilisation of hand-held video camera. To achieve steady flight of an aerodynamic vehicle, it is essential to control the rotation of vehicle about all the three axes by properly designed servo mechanism for correcting the disturbances received through gyroscope. Recently, system requirements have made increasing demands on gyro performance and environment capability. Further, performance improvements have resulted with increased emphasis on reduction in size and power consumption as well as on reliability improvement and reduction in manufacturing cost. Inspite of very high performance already achieved, there will be continued improvement in gyro technology. As a vibratory gyroscope incorporates sensing and actuation linked by control functions, it may be regarded as a smart sensor. Solid-state nature of 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.

2. GYRO SENSOR TECHNOLOGY

Based on the design, gyroscopes are classified as mechanical, optical, and vibrating structure, and based on the performance, gyroscopes are classified as inertial grade, tactical grade, and rate grade. The precession, the Sagnac effect, and the Coriolis effect are used for the detection of angular rate. The major difference between the conventional mechanical gyroscope and vibrating gyroscope is that instead of spinning wheel as used in the

---

Revised 16 September 2006

former, the latter uses momentum of a vibrating elastic body. In vibratory gyroscopes, an elastic body or 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 use of two vibration modes, primary, which arises due to excitation, and secondary, which arises due to Coriolis force. By simply placing a piezoelectric gyroscope in a desired location or position, on an object, the angular velocity of the object can be accurately detected, unaffected by the mounting position.

Early research on piezoelectric gyroscope was motivated by military applications for designing high-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 an increasingly decreased size, improved accuracy, and reduced prices. 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[2]. As the technology develops and vibratory gyroscopes become smaller, cheaper, and perform better, many more applications will become possible. Generally, the precession-based sensors are used for ships and Sagnac effect sensors are used for airplanes. Sensors based on Coriolis effect are suitable for compact applications.

2.1 Mechanical Gyroscope

Mechanical gyroscope, a well-known device, consists of a spinning mass, usually a heavy disk called a rotor, mounted on the base with a spin axis positioned through the centre of the rotor. The rotor is mounted within the gimbals with its axis free to turn, but maintains a fixed direction. The rotation in the frame imparts a torque (rotation) to the spinning disk, which precesses (rotates) as a result. Practical uses usually limit the movement to measure only one axis of rotation (roll, pitch or yaw). The gyroscope frame is responsible for stabilisation of the platform. Three rate gyroscopes are fitted in the frame with their input axes mutually perpendicular, i.e., pitch, yaw and roll are detected by the three gyroscopes input axis. The deflection of gyroscope is converted into a signal voltage that when amplified, drives corresponding servomotors via a gear train to rotate the frame back to its original position. Autopilot basically consists of three devices, each of which detects disturbances by moving the appropriate control surface. In such designs, a rate gyroscope detects disturbances. The mechanical gyroscope has moving parts such as the ball bearings and high-speed rotor to obtain high angular momentum. This feature of the mechanical gyroscope affects the life and reliability of the device. Besides this, the mechanical gyroscope is heavy and occupies large space, which makes it unsuitable for applications with weight and space constraints.

2.2 Optical Gyroscope

The basis for detection of rotation rate by optical methods without an external reference is the Sagnac effect. The first practical demonstration of the Sagnac effect was the ring laser gyro in 1963. In optical gyroscope, two laser beams move in opposite directions in the same ring path. Any change in the rotation of the system causes a difference in the path of these two beams. Detection of very small changes is possible using interferometric measurements. Optical gyroscopes, therefore do not depend on the acceleration as gyros in the mechanical group. The two types of optical gyroscopes, laser gyroscopes and fibre optic gyroscopes, are based on the Sagnac effect.

Ring laser gyros are based on active Sagnac effect. Generally, it makes use of triangular laser cavity having three mirrors at the three vertices. There are two active optical oscillators internal to the loop so that lasing occurs in both the directions, creating clockwise and anti-clockwise laser beams. Cavity length is controlled by servoing one mirror and the other mirror allows enough leakage so that two counter-rotating beams form an interference pattern on photodetector array. Inertial rotation of device changes effective cavity lengths of clockwise and counter-clockwise beams, causing an effective relative frequency change at the detector. Scale factor is proportional to the area enclosed by laser path. Effect has to be enhanced greatly to make a practical rotation sensor with good sensitivity.

The major limitation of ring laser gyro is mode locking between counter-propagating beams, creating a dead zone at low-rotation rate since oscillations are of very high frequency (5 x 10^{14} Hz) and with very small frequency difference. The backscattering of the mirrors is the main source of coupling. The problem of deadlock has been resolved using mechanical dither to vibrate the gyros at a rate outside of dead zone. Dithered gyros have bias stability better than 10^{-2} deg/h and scale factor accuracy better than 1 ppm for a dynamic range of 400 deg/s. Ring laser gyro is a very complex technology. To avoid locking, passive ring cavity is being used. In case of ring laser gyro, laser requirement makes the gyroscope bulky and costly.

Fibre optic gyros are passive optical gyros and make use of advances in four distinct fields, i.e. light sources, beam-conditioning optics, optical fibre, signal detection and conditioning. Rotation of the coil produces Sagnac shifts in all the beams that have equal magnitudes but opposite signs. The measurement of the phase difference between the two optical waves at the interferometer output yields the rotation rate, which is linearly proportional to Sagnac phase shift. Accurate measurement of rotation rate requires differential phase shift between counter-propagating waves to be virtually eliminated from all sources other than rotation. The technological challenge has been the measurement of differential phase shift (10^{-7} radian). Optical reciprocity of the two beams is a mandatory requirement, which means two counter-propagation waves following exactly the same optical path. Single-mode fibre rather than multi-mode fibre should be used so that both the path of optical waves and phase fronts are defined uniquely. The effective paths of two beams can be different if the two waves have different polarisation at any point.

Fibre conducts light of different polarisation at different speeds, a property called birefringence. Use of modal polarisation filter becomes necessary so that polarisation of the two beams can be kept identical at all points. Two optical beams satisfying reciprocity consideration travel equal distances. Light source of very short coherent length is required. For this purpose multi-mode laser diodes were used earlier, whereas at present, super-luminescent diodes as low-coherence source are used. Another requirement of fibre optic gyro technology is that of complex signal processing, because, detector output current is squared cosine function of phase difference between two beams, so as to have high sensitivity and linear output. Differential phase shift varies with input rotation rate but gyro output will not be linear without special design. Inherently nonlinear response with maximums and minimums, i.e., detector current is very insensitive to small phase shift changes near zero rotation rate as well as to rotation rates corresponding to other minimums and maximums. Symmetry of the response curve provides no distinction between rotations in the two different directions.

Both problems are solved by providing bias-non reciprocal phase shift between the waves. Common biasing approach-sinusoidal modulation of phase difference between two waves has been used. Another requirement is searching for wide dynamic range, i.e. 10^{-2} deg/h to 1000 deg/s. Close-loop gyro uses non-reciprocal phase shift (NRPS) in fibre-sensing coil which applies a controlled amount of differential phase shift to the counter-propagating waves. Non-reciprocal phase shift driven by servo amplifier, provides a non-reciprocal phase shift that is equal and opposite to the Sagnac phase shift caused by rotation. Net non-reciprocal phase shift in gyro is always zero.

Optical gyroscopes are considered to be the most accurate, out of which ring laser gyros have demonstrated inertial-grade performance, while fibre optic gyros are mainly used for tactical-grade applications. However, optical gyroscopes are too expensive and bulky for many applications.

2.3 Piezoelectric Gyroscope

Piezoelectric vibratory gyroscopes have received a lot of attention[1-8] during the past few years, as many applications exist for these miniature devices. These can be used either as a low-cost companion with accelerometers to provide heading information for inertial navigation purposes, or stand alone and can be used in other applications where rotation rate needs to be measured; some consumer electronic applications such as stabilisation of pictures in digital video cameras and inertial mouse in computers; robotics applications; and, a wide range of military applications such as guidance of missiles and platform stabilisation. Much of the effort in developing these gyroscopes has concentrated on rate-grade devices for automotive applications, which requires a rotation rate resolution and bias stability of about 0.5 deg/s. This gyro is suitable for mass production and is almost maintenance-free.

In vibratory gyroscopes, an elastic body or resonator is forced to vibrate in a flexible mode. 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 use of two vibration modes of a piezoelectric material. In these two modes, material particles move in a perpendicular direction so that Coriolis force, which arises in a rotating frame of reference, couples the two modes. Furthermore, the resonant frequencies of these two modes are very close for the gyroscope to work at resonance for maximum sensitivity.

Two modes satisfying these two criteria are fundamental to piezoelectric gyroscope and are called a pair of gyroscopic modes. When a piezoelectric gyroscope is excited into vibration in the primary mode, by an applied alternating voltage and attached to a rotating body, the Coriolis force will couple energy from the primary mode of vibration into a secondary mode and excite this secondary mode, as shown in Fig.1. This transfer of energy provides a measure of the applied rotation rate. Due to this operating principle, this type of gyroscope is known as vibratory gyroscope. 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 latter vibration is directly proportional to the applied angular rate.

These resonators can be of various geometric structures depending upon the designs. The resonators may be divided into two classes depending on the modes of vibration used during operation as a gyroscope. In the first class of resonators, the Coriolis coupling between two dissimilar vibration modes of different natural frequency, is measured. The resonators forming the second class have two orthogonal vibration modes, which have the same shapes and identical natural frequencies, in the absence of imperfections. Various methods have been applied to excite and sense the resonator vibrations. These methods include electromagnetism, electrostatics, and piezoelectricity. Gyroscope based piezoelectric actuation and sensing has been discussed in this paper. Several types of vibratory piezoelectric gyroscopes have been developed. These can be broadly divided into three categories as follows:

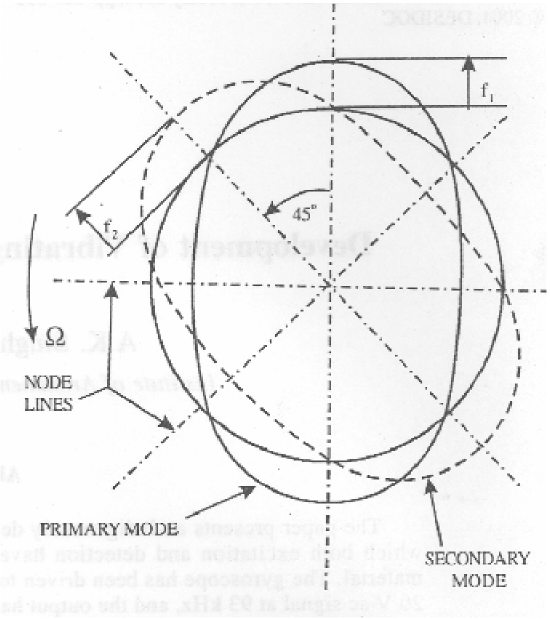

Figure 1. Radial displacements of primary and secondary (gyroscopic) modes of operation vibration caused by the Coriolis force.

(i) Simple oscillator - string or beam

(ii) Balanced oscillator - tuning fork or H structure

(iii) Shell resonator - cylinder, ring or disc

2.3.1 Beam-type Piezoelectric Vibrating Gyroscope

Gates[9] proposed first vibrating beam structure gyroscope made up of Ni-Span-C, rounded outwards from the nodes and held by o-ring clamps at both nodal points. The beam was excited by attaching piezoelectric elements. The force for driving the beam was applied through piezoelectric transducers bonded to the beam's surface in the drive plane.

Transducers made of PZT are thin rectangular plates and bonded to each of the other three beam's surfaces of the rectangular beam. The transducer on one of the faces at right angle to the drive face, senses the Coriolis-induced vibrations and provides rotation rate on the read out. The transducer on the face parallel to the drive face is a feedback transducer used in an electronic drive circuit to keep the amplitude constant and vibrating at the mechanical resonant frequency. The transducer opposite to the read out transducer is connected to a circuit that damps the beam electronically. There are some inherent disadvantages common to metallic bar-type gyroscopes. Since different natural materials, metal, and ceramics, are joined together, sensor performance varies depending on the jointing status. The processing method and wiring from the electrode form 3-D structures, and hence, involve complex production processes. Designs based on pendulums, vibrating strings or cantilever beams are also sensitive to linear accelerations.

A large number of papers have been reported[10-13] on vibrating beam structure gyros for their analysis and improved performance. Kudo,[10] *et al.* proposed null signal reduction and response improvement by active damping and analysed their transitional response for stepped angular velocity. Sato,[11-13] *et al.* considered parallel beam structure and analysed it using FEM and proposed a suppression method of mechanical coupling for gyroscope application. Quick[14] also analysed vibrating string as an angular-motion sensor.

2.3.2 Tuning Fork Gyroscope

An early tuning fork design has been described by Hunt and Hobbs[15]. The tuning fork, as illustrated in Fig. 2, consists of two tines connected to a junction bar. In operation, the tines are differentially resonated to a fixed amplitude, and when rotated, Coriolis force causes a differential sinusoidal force to develop on the individual tines, orthogonal to the main vibration. This force is detected either as differential bending of the tuning fork tines or as a torsional vibration of the tuning fork stem. The actuation mechanism used for driving the vibrating structure into resonance is primarily piezoelectric. To sense the Coriolis-induced vibrations in the second mode, a piezoelectric detection is used. Soderkvist[16] developed a tuning fork rate sensor made out of single piece of quartz and analysed the performance using piezoelectric beam theory. Wakatsuki and Tanaka[17] proposed a single-crystal tuning fork gyroscope made out of $LiTaO_3$.

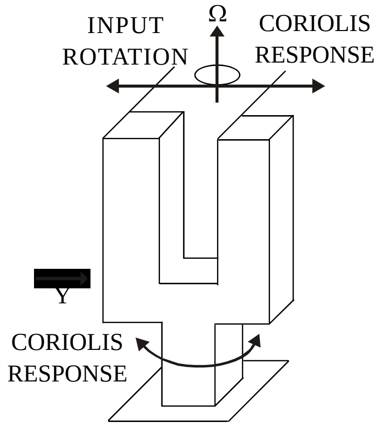

Figure 2. Tuning fork structure vibratory gyro with piezoelectric elements.

2.3.3 H Structure Gyroscope

A balanced form of tuning fork structure gyro is H structure[18-20]. Nonomura,[18] *et al.* developed H shaped structure gyro and reported that these gyros show wide temperature stability, better sensitivity, reduced offset, and nonlinearity. Chiba and Wakatsuki[19] reported an H-type single-crystal piezoelectric gyroscope of $LiTaO_3$ and also proposed an automatic compensation method for the temperature characteristics and sensitivity.

2.3.4 Disc-type Gyroscope

This category of gyros are flat structures i.e., disk and plate. The design of a piezoelectric disc gyroscope has been discussed by Burdes[21]. Tamara,[22] *et al.* developed a vibratory gyro sensor using a flexural same-form double-mode disk resonator having two-elements metal disc for drive and pickup with additional inertia for sensitivity improvement. In the design of disk gyro sensors[23,24] electrodes were deposited on both sides of disk for drive and pickoff (Fig. 3). This was achieved by making the disc out of a piezoelectric material having eight electrodes on the top and single electrode at the bottom[24]. The response of gyroscope to constant and harmonic rates is analyzed by driving the equations of motion of disk[21]. Abe[25], *et al.* and Kaida and Inoue[6] have proposed, respectively, vibrating gyro sensors based on thickness shear vibrations of a piezoelectric ceramic plate and second harmonic thickness extensional vibration in a two-layered piezoelectric plate.

2.3.5 Cylinder Gyroscope

The gyroscope is based on a uniform vibrating cylinder[26-27], which is clamped at one end and mounted on a pedestal so that the other end is free to vibrate. The cylinder is assumed to be thin and perfectly axis-symmetric. On the outer surface, eight identical equi-spaced electrodes Nos 1 to 8 are attached which are electrically connected in pairs; 1 with 5, 2 with 6, 3 with 7, and 4 with 9. A periodic driving force is applied to electrodes pair 1 and 5 at the resonance frequency of the cylinder. The response is measured across electrodes 3 and 7 (Fig. 4).

A second pair of measurement electrodes were arranged to be set on the + 45° and – 45° nodal lines of the forced circumferential mode and would ideally produce no output as a result of the oscillator vibration. When the cylinder was rotated about its central axis, the Coriolis inertia force would generate a secondary motion. This new vibration would generate an output on electrodes pair 2 and 6, proportional to the angular rotation velocity. If the voltage applied to electrodes pair 2 and 6 is provided by introducing negative feedback from electrodes pair 4 and 8 it would be possible to drive the secondary motion to a null value. This is necessary so that the gyroscope can respond to rapid changes in angular velocity The voltage applied at electrodes pair 2 and 6 was taken as a measure of the applied rate of turn. Yang and Fang[26] used ceramic tube poled in the thickness direction, operating based on flexural vibration mode in perpendicular direction, and examined voltage sensitivity

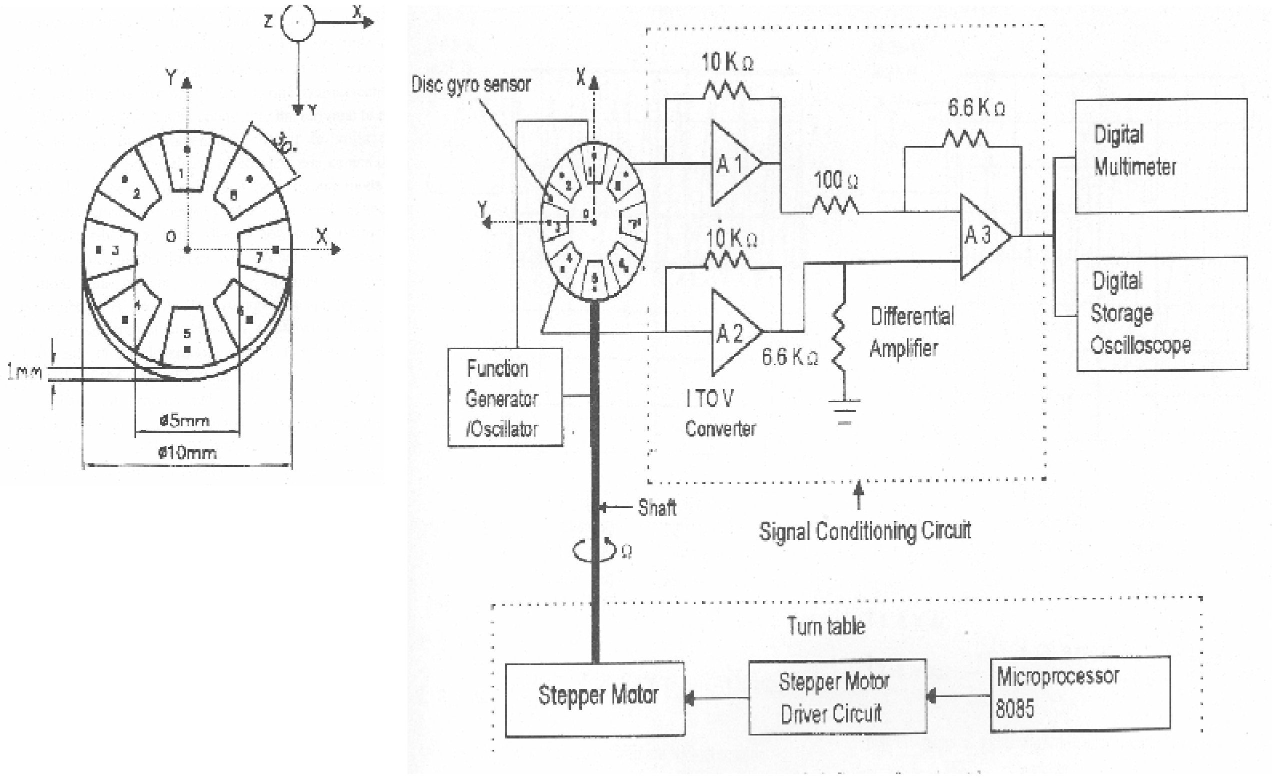

Figure 3. Piezoelectric disc structure gyroscope sensing element, signal conditioning, and its test setup.

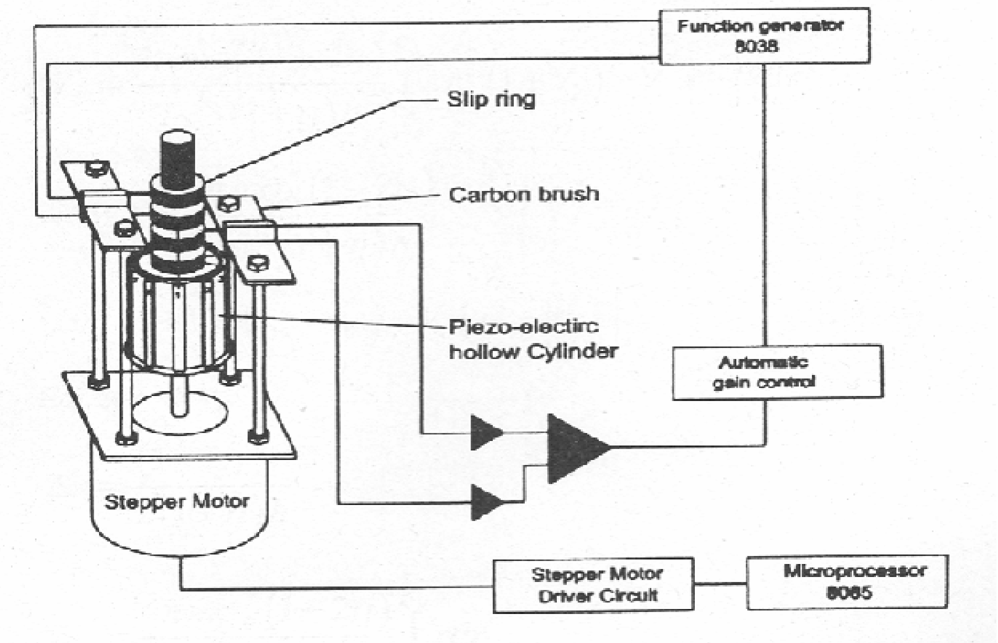

Figure 4. Experimental setup of piezoelectric cylinder gyroscope, turn table test setup, excitation and detection circuit.

and its dependence on various geometric and physical parameters.

3. DISCUSSION AND CONCLUSION

There are various parts in a vibrating structure piezoelectric gyroscope and each part contributes to the output. The drive circuit applies a controlled vibration to the transducer/sensing element. The transducer transfers a portion of the driven vibration to a sensing system when an angular motion is applied. The sense circuit transforms the sensed vibration signal to produce an output signal.

The theory behind the operation of vibrating structure piezoelectric gyroscopes has been well-understood and a large numbers of papers have appeared in the literature.[17, 21, 27-31] Brudess[21] has analysed disc gyro structure whereas Wakatsuki and Tanaka[17] did simulation of a single-crystal tuning fork gyroscope using FEM for vibration modes. Yang[28], *et al.* analysed one-dimensional equations for a piezoelectric ring, beam, and two-dimensional equations for piezoelectric shells. The study of circular ring piezoelectric gyroscope makes use of coupled external and flexural vibrations, a beam bimorph gyroscope uses flexural vibration, a circular cylindrical shell uses radial and torsional vibrations. Resonant frequency, voltage sensing signals and their dependence on the driving frequency, rotation rate, impedance of the circuit and material, have been analysed. Yang[29], *et al.* and Yang and Fang[30], have dealt with one-dimensional equations for a piezoelectric ring and application in a gyroscope, and beam with piezoelectric film as an angular-rate sensor. Jongwan,[31] *et al.* presented a rigorous analysis of vibratory angular-rate sensor using polarised piezoelectric ceramic bimorph plate.

In literature, one may find certain variations in the configurations discussed, like single-beam, parallel-beam gyros have also been proposed. Another form of beam-type gyro is string, being used as an angular-motion sensor. The various configurations discussed so far are single-axis rate sensor but multi-axes rate sensors have also been proposed. Recently, multi-axes rate sensor has been proposed[32] which is based on ring structure having two in plane mode of vibration and identical natural frequencies.

The piezoelectric gyro sensor technology has matured and is inherently robust and reliable. Focus of the current research is on compensation of vibration and temperature because these rate sensors are sensitive to vibrations, which reduces at low frequency vibration, and temperature, which is primarily due to variation of piezoelectric coefficients over temperature. It is proposed to use servo amplifier to remove the dc level shift raised due to temperature-related drift effects. Variation effects can be taken out of the drive system by automatic gain control. An extensive analysis of literature has shown several design improvements, i.e., electrode configuration, circuitry for improved bias stability, and improved scale factor. Material selection needs to be examined to have increased bandwidth. The mechanical Q of the material can be used to expand bandwidth and the relationships among resonant frequency, bandwidth, and tuning.

ACKNOWLEDGEMENT

Author is thankful to the Vice Chancellor, Defence Institute of Advanced Technology, Pune, for granting permission to publish this work.

REFERENCES

1. Langmaid, C. Vibrating structure gyroscopes. *Sensors Review*, 1996, **16**, 14-17.
2. Tamura, H.; Tomikawa, Y.; Kikuchi, T. & Sugawara, S. Vibratory gyro sensor using a flexural same-form double-mode disk resonator. *Jpn. J. Appl. Phys.*, 1998, **37**, 2859-863.
3. Abe, H.; Yoshida, T. & Turuga, K. Piezoelectric ceramic cylinder vibratory gyroscope. *Jpn. J. Appl. Phys.*, 1992, **31**, 3061-063.
4. Kristiansen, D. Modelling of cylinder gyroscopes and observer design for nonlinear oscillations. Norwegian University of Science & Technology, Trondhem, 2000. PhD Thesis.
5. Aizawa, H.; Sugawara, S. & Terada, J. Construction of low-frequency flat-type piezoelectric vibrating gyroscope. *Jpn. J. Appl. Phys.*, 2001, **40**, 5751-755.
6. Kaida, H. & Inoue, J. Strip-type resonators using second harmonic thickness extensional vibration. *Jpn. J. Appl. Phys.*, 2001, **40**, 3680-682.
7. Ono, K.; Yachi, M. & Wakatsuki, N. H-type single-crystal piezoelectric gyroscope of an oppositely polarised $LiNbO_3$ plate. *Jpn. J. Appl. Phys.*, 2001, **40**, 3699-703.
8. Tawari, R. & Singh, A. K. Development of a piezoelectric vibrating cylinder-type gyroscope. *In* Sensors for Industry Conference, 8-10 February, 2005. Houston, Texas, USA, 2005.
9. Gates, W.D. Vibrating angular rate sensor may threaten the gyroscope. *Electronics*, 1968, **41**, 130-35.
10. Kudo, S.; Suguwara, S. & Wakatuki, N. Improvement of transitional response characteristics of a piezoelectric vibratory gyroscope. *Jpn. J. Appl. Phys.*, 1996, **35**, 3055-058.
11. Sato, H.; Fukuda,T.; Arai, F.; Iwata, H. & Itoigawa, K. Analysis of parallel beam gyroscopes. *In* Proceedings IEEE International Conference on Robotics and Automation, Detroit, Michigan, May 1999. pp.1632-637.
12. Sato, H.; Fukuda, T.; Arai, F.; Itoigawa, K. & Tsukahara, Y. Improvement of sensing and actuating property of parallel beam gyroscope. *In IEEE* International Symposium on Micromechatronics and Human Sciences, 1999. pp. 249-54.
13. Sato, H.; Fukuda, T.; Arai, F.; Itoigawa, K. & Tsukahara, Y. Parallel beam sensor actuator unit and its application to gyroscope. *IEEE/ ASME Trans. Mechatronics*, 2000, **5**(3), 266- 72.
14. Quick, W.H. Theory of the vibrating string as an angular motion sensor. *Trans. J. Appl. Mech.*, 1964, 523-34.
15. Hunt, G.H. & Hobbs, A.E.W. Development of an accurate tuning fork gyroscope. *In* Symposium on Gyros, Proceedings of Institute of Mechanical Engineering,Vol. 17, 1964, pp.523-34.
16. Soderkvist, J. Piezoelectric beams and vibrating angular rate sensors. *IEEE Trans. Ultrasonics, Ferroelec. Freq. Cont.*, 1991, **38**(3), 271-80.
17. Wakatsuki, N. & Tanaka, H. Finite element method analysis of single crystal tuning fork gyroscope for suppression of its inner leakage coupling. *Jpn. J. Appl. Phys.*, 1997, **36**, 3037-040.

18. Nanomura, Y.; Fujiyoshi, M.; Omura,Y.; Tsukada, K.; & Okuwa, M. Quartz rate gyro sensor for automotive control. *Sensors Actuators A*, 2004, **110**, 136-41.

19. Chiba, M. & Wakatsuki, N. Experimental validation of temperature self-compensation for $LiTaO_3$ piezoelectric gyroscope. *In* IEEE Ultrasonic Symposium, 2000. pp. 883-88.

20. Wakatuki, N.; Kudo, S.; Sato, Y. & Tanaka, H. A new approach to piezoelectric crystal gyroscopes for higher sensitivity. *In* IEEE Ultrasonic Symposium, 1998. pp. 477-80.

21. Brudess, J.S. The theory of a piezoelectric disc gyroscope. *IEEE Trans. Aerospace Elect. Syst.*, 1986, **22**(4), 410-18.

22. Tamara, H.; Tomikawa, Y.; Kikuchi, T. & Sugawara, S. Vibratory gyro sensor using a flexure same form double-mode disc resonator. *Jpn. J. Appl. Phys.*, 1988, **37**, 2859-863.

23. Singh, A.K. & Gorain, U.K. Development of vibrating disc piezoelectric gyroscope. *Def. Sci. J.*, 2004, **54**(3), 387-93.

24. Singh, A.K. & Deo, V. Vibrating single crystal piezoelectric disc gyroscope. *Ind. J. Pure Appl. Phys.*, 2004, **42**, 452-58.

25. Abe, H.; Yoshida, T.; Ishikawa, T.; Miyazaki, N. & Watanabe, H. Trapped energy gyroscopes using thickness shear vibrations in a partially-polarised piezoelectric ceramic plate. *Jpn. J. Appl. Phys.*, 1998, **37**, 5345-348.

26. Yang, J.S. & Fang, H.Y. A new ceramic tube piezoelectric gyroscope. *Sensors Actuators* A, 2003, **107**, 42-49.

27. Singh, A.K. Vibrating structure piezoelectric hollow cylinder gyroscope. *Ind. J. Engg. Mater. Sci.*, 2005, **12**, 7-11.

28. Yang, J.S.; Fang, H.Y. & Jiang, Q. Analysis of a few piezoelectric gyroscopes. *IEEE Proceedings*, 2000, 79-86.

29. Yang, J. S.; Fang,, H.Y. & Jiang, Q. One-dimensional equations for a piezoelectric ring and applications in a gyroscope. *IEEE Trans. Ultrasonics Freq. Cont.*, 2001, **485**, 1275-282.

30. Yang, J.S. & Fang, H.Y. Analysis of a Rotating elastic beam with piezoelectric films as an angular rate sensor. *IEEE Trans. Ultrasonics Freq. Cont.*, 2002, **496**, 798-804.

31. Jongwan, S.K.;Tiersten, H.F. & Scarton, H.A. An analysis of a vibratory angular-rate gyroscope using polarised piezoelectric bimorph plates. Part 1: Derivation of variational equations in the absence of angular velocity. *J. Sound Vib.*, 2005, **280**, 263-87.

32. Rourke, A.K.; Mcwilliam, S. & Foke, C.H.J. Frequency trimming of a vibrating ring-based multi-axes rate sensor. *J. Sound Vib.*, 2005, **280**, 495-30.

Contributor

Dr A.K. Singh did his MSc (Electronics) from the Agra Univiersity in 1986 and received his PhD from the University of Rajasthan, Jaipur, in 2002. He joined DRDO in 1991 and presently working in the Department of Aerospace Engineering at the Defence Institute of Advanced Technology, Pune. His research interests include: Piezoelectric sensors and actuators, PC-based instrumentation, thermal studies of materials and nano fluids. He is the reciepient of *DRDO Scientist of the Year Award* (2005), for his contributions in the field of instrumentation.