CORIOLIS GYRO CONFIGURATION EFFECTS ON NOISE AND DRIFT PERFORMANCE

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September 17, 2002

Abstract

The use of vibratory gyros to supplement non-inertial navigation systems is limited almost entirely by noise and drift properties of those gyros. This paper examines the nature of these performance characteristics to show how size, material and configuration can be specified to select or make the optimum gyro for the application. The gyros tested are the quartz tuning fork, piezoceramic tuning fork, silicon ring, piezoceramic cup, and piezoceramic bar types.

The comparison of the spectral analysis data and the size, material and configuration attributes of the associated gyro were used to construct an empirical formula that predicts solid-state gyro bias noise to a high degree of accuracy.

Introduction

Watson Industries, Inc. is in its twenty-third year of operations and has provided solid state gyro sensors for a wide range of projects including stabilization, control and instrumentation for military and civilian projects worldwide. These projects require a wide range of performance specifications, but the requirement for stability has always been a high priority.

The integration of a solid-state gyro system to GPS brings special requirements. These gyros need to have stability in the short to mid term, but the long term would not be required to cover a GPS outage. The search for tools to define such stability has developed into finding tools to predict drift performance.

Gyro Types

The tradition in spinning wheel gyros is that better performance comes from more momentum. More mass or higher spin speed is how this is done. If the gyro is doubled in size in all dimensions, the mass increases by eight and the rim speed doubles with a constant RPM. This is a total of a sixteen-fold increase in momentum.

The same principle holds for vibratory gyros as well, but the means are different. When the size is doubled the mass increases, but the speed of the sensing mass is a function of the natural frequency and the displacement which would change.

In an earlier paper [1], the relationship for size *vs.* medium term drift was shown for a tuning fork configuration to be approximately the fifth power of size if the configuration and material are constant. This together with the above indicates that the performance of a gyro might be predicted given certain measurements. This result could be used ether to direct gyro improvement or for gyro selection for an application.

To cover a diverse group of gyro configurations, the definition of the parameters used must be widely applicable. The operating frequency and the drive mode "Q" are easy to define, but the relative size and the sense mode "Q" are not so direct.

D.D. Lynch has shown that the critical dimension in the size of a gyro is the "pendulum" length [2]. This is defined here as the length of the sense mechanism. The configurations being examined here are described below.

Bar and Rod Configuration:

The bar or rod is a simple structure mounted on two flexible supports at the two nodes of its primary oscillation mode. The designers of both of these types of gyros have elected to connect sensing electrodes only between the nodes.

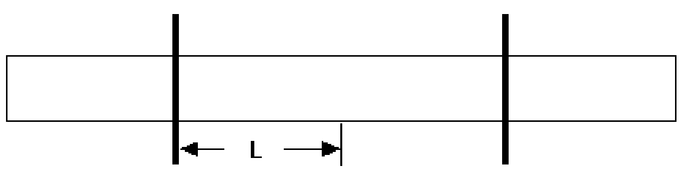

Figure 1. Bar or Rod Gyro

The result is that there are two pendulums with a length of one half the distance between the nodes. The drive and sense Q are the Q of the material if the node support is effective.

Fork Configuration:

The tuning fork is a structure mounted at the node of its primary oscillation mode. There are two obvious sensing structures with a well-defined sensor pendulum length.

The drive Q is that of the material minus losses, but since the sense elements are operating well below their natural frequency, the sense Q is one.

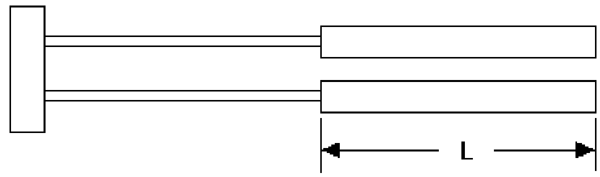

Figure 2. Tuning Fork Configuration

"H" Fork Configuration:

The "H" fork consists of a driven resonant fork and a pair of torque sensing tines. This configuration provides significant isolation between the drive and sensing systems. There are effectively two sensing elements of a definable length. As with the fork above, the drive Q is that of the material and the sense Q is one.

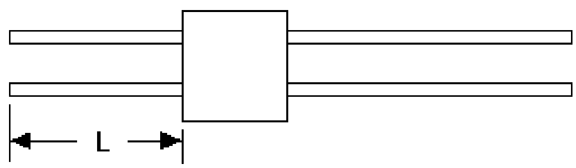

Figure 3. H Fork Configuration

Cup Configuration:

The cup configuration consists of four drive electrodes and four sense electrodes alternating and evenly spaced around the circumference of a cup wall. This design currently connects only two electrodes for sensing as the other two sense electrodes are used for torque drivers. Each sense area is, however, given signals from both sides and as such consists of two pendulum lengths each with the length being one eight of the circumference each. There are then four effective sense pendulums whose length is 0.39 times the diameter of the cup.

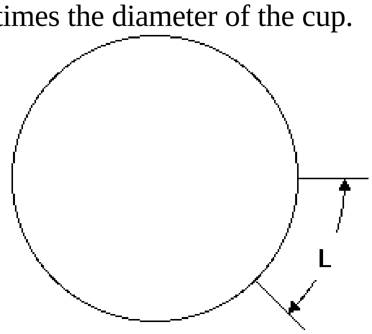

Figure 4. Cup or Ring Configuration

The drive Q is that of the material. The sense Q, however, is controlled by a torque feedback system that electrically damps vibration [3]. The sense Q is then the drive frequency divided by twice the sense bandwidth.

Ring Configuration:

The ring configuration is the same as the cup configuration. There are again four effective sense pendulums whose length is 0.39 times the diameter of the ring and the Q is found as above.

Testing

There are traditional ways to measure noise and drift in gyros. One that has come from the ring laser gyro field is Allen variance analysis. Allen variance analysis actually was developed for atomic clock design analysis and deals with long-term drift [4]. The needs of GPS stabilization are shorter term and simpler than that.

What was done is testing over a period of 2600 seconds (more than 40 minutes). Noise and alias response was addressed by using a twenty Hertz low pass input filter with 100 sample per second data rate and sixteen sample averaging. Resolution was maintained by using a 16-bit analog to digital converter. The input range was generally limited to +/- 2 degrees per second (except for the more drifty gyros).

This is essentially the view of the stability of the gyro under test as a GPS system might see it in terms of time frame and resolution.

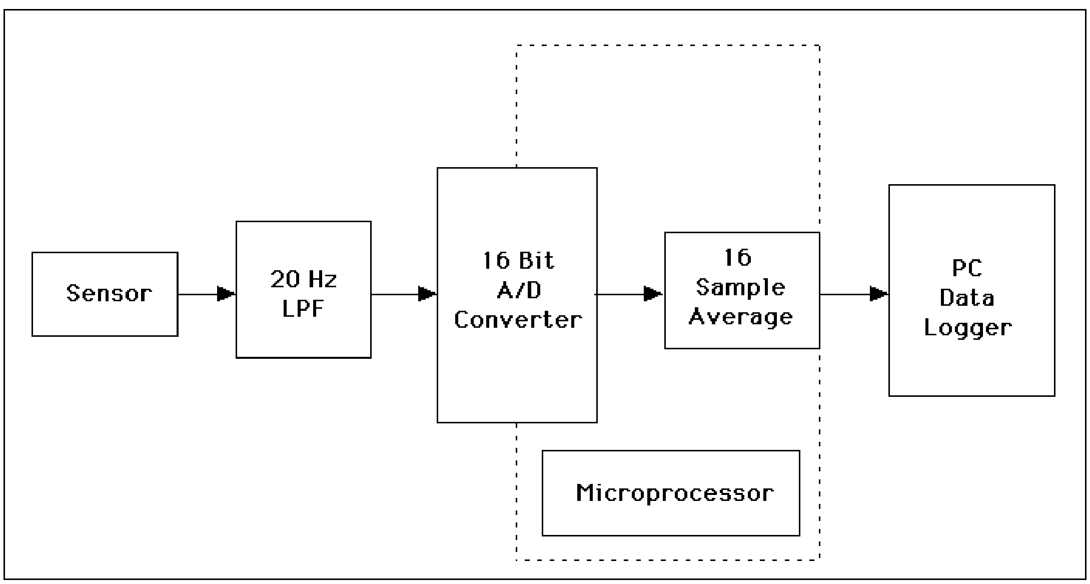

Figure 5. Data Acquisition system

The range of the data collected is demonstrated in the two examples shown below.

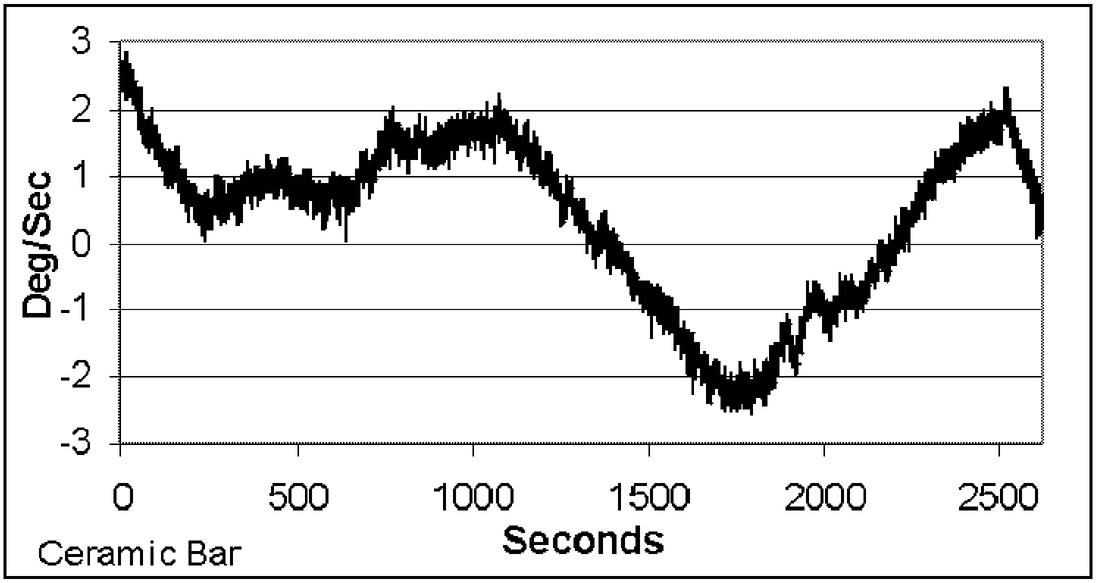

Figure 6. Ceramic Bar Raw Data

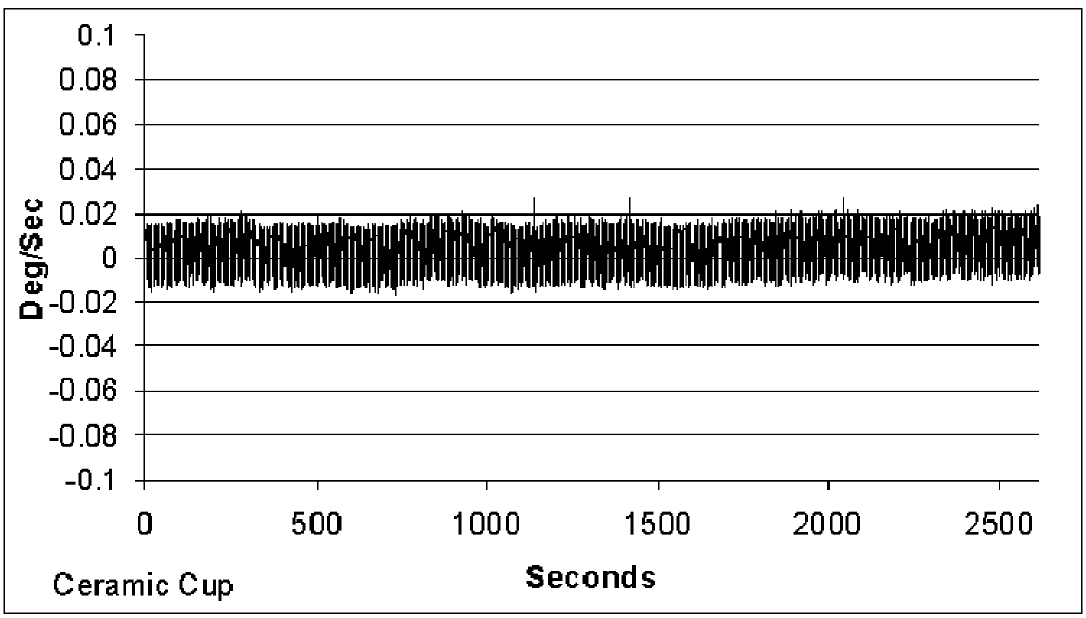

Figure 7. Ceramic Cup Raw Data

Data Reduction

The data was converted to the frequency domain using Fourier Transform methods. Then the data was converted to a period based data set. The result was filtered to get a solid trend.

The minimum values of the spectrum for some of the gyros are known from manufacturer-supplied data (Bias Drift). These known points were used to calculate a normalization factor that was used to calibrate the curve as shown below.

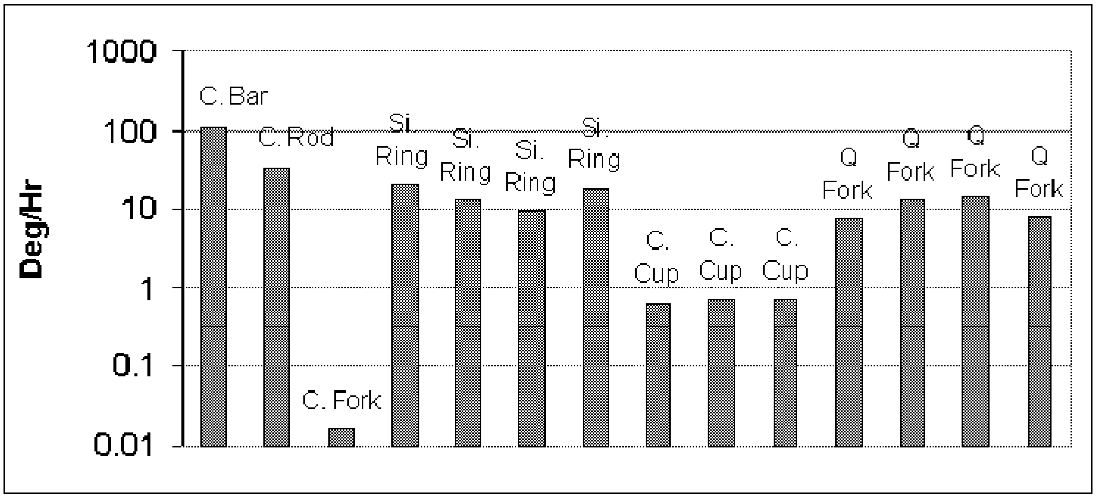

Figure 8. Minimum Bias Noise Summary

The normalized spectrum curves *vs.* period that resulted are shown below.

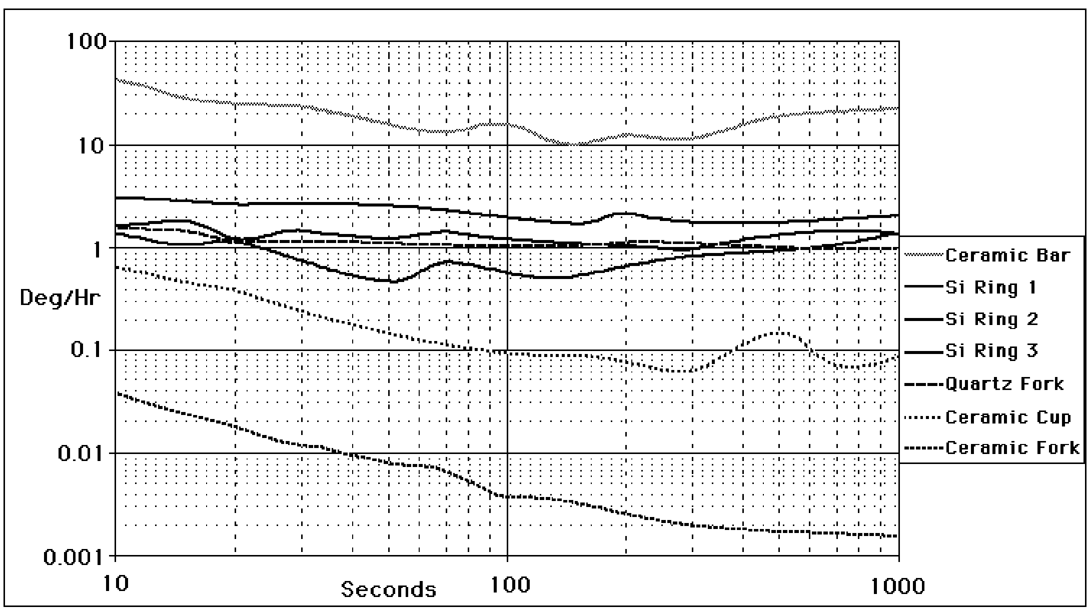

Figure 9. Bias Noise Spectrum

Noise Mechanisms

The size, as mentioned before, is strongly coupled to performance in the mass and velocity of the sense system. There are also moment arm effects on the sense system that increases sensitivity.

Quantum-like effects are also a function of size. It is not uncommon for one degree per second to produce less than a molecule of sense displacement in some gyros. Additionally, defects and/or grain sizes become more significant as size is reduced.

The increased width of the sense area will produce more rate signal in a gyro [5]. However, in most structures this width increase will also allow more drive system induces errors which will increase noise.

It has been found that an increase in sense system Q will reduce bias noise [3]. The equation that relates the bandwidth to the system frequency and sense Q is [5]:

$$B_{WS} = F_D/(2Q_S)$$

Where:

B_{WS} = Bandwidth of the gyro sense response
F_D = Drive frequency
Q_S = Q of the sense system

From this we can infer that decreasing the system frequency or increasing the sense Q can decrease the bias noise.

A similar equation for the drive system is:

$$B_{WD} = F_D/(2Q_D)$$

Where:

B_{WD} = Bandwidth of the gyro drive response
F_D = Drive frequency
Q_D = Q of the drive system

The drive bandwidth is important because noise in the drive system will certainly migrate into the sense system. As such, the bias noise would be reduced if the system frequency was reduced or the sense Q increased.

The number of effective sensing mechanisms is also significant. More sensors mean more signal.

With these relationships established, an empirical formula for predicting bias noise can be developed. The relevant parameters of the gyros under examination were:

Type	Drive Freq.	Pend. Length	Q Drive	Q Sense	Sense Plates
	(Hz)	(mm)			
Ceramic Bar	22070	3.5	800	800	2
Ceramic Rod	24730	3.5	800	800	2
Ceramic Fork	366	14.5	26	1	2
Silicon Ring	14030	2.35	10000	500	4
Silicon Ring	13780	2.35	10000	700	4
Silicon Ring	18150	2.35	10000	750	4
Silicon Ring	14000	2.35	10000	450	4
Ceramic Cup	8330	7.1	800	52	4
Ceramic Cup	8310	7.1	800	52	4
Ceramic Cup	8250	7.1	800	52	4
Quartz Dual Fork	10750			1	2
Quartz Dual Fork	10750			1	2
Quartz Dual Fork	10750			1	2
Quartz Dual Fork	10750			1	2

Starting with the assumption that the fifth power of length was involved, estimates of bias noise were made and iterated until the following formula resulted:

$$NB = K*(FD^2)/((L^6)*QD*QS*N)$$

Where: NB = Bias Noise in degrees per hour.
K = Normalizing constant.
FD = Drive frequency in Hertz.
L = Pendulum length of the sense system in millimeters.
QD = Drive Q.
QS = Sense Q.
N = Number of effective sense units.

This formula was used to calculate bias noise for a comparison of the results to the test data as shown below:

Type	Calculated Noise (Deg/Hr)	Tested Noise (Deg/Hr)
Ceramic Bar	46.99	107.4
Ceramic Rod	59.00	34.28
Ceramic Fork	0.0124	0.0163
Silicon Ring	13.26	21.168
Silicon Ring	9.14	12.784
Silicon Ring	14.79	9.705
Silicon Ring	14.67	17.91
Ceramic Cup	0.7389	0.635
Ceramic Cup	0.7354	0.741
Ceramic Cup	0.7248	0.741
Quartz H Fork		7.56
Quartz H Fork		12.61
Quartz H Fork		14.11
Quartz H Fork		8.064

The H Fork parameters did not include the sense pendulum length and its Q was uncertain so the formula could not be used to make a predicted bias noise. However, working backward from the test data gives a sense pendulum length of 3.5 mm if a Q of one million is assumed. These are likely values.

The rest of the data shows an extremely strong correlation between calculated data and the test data:

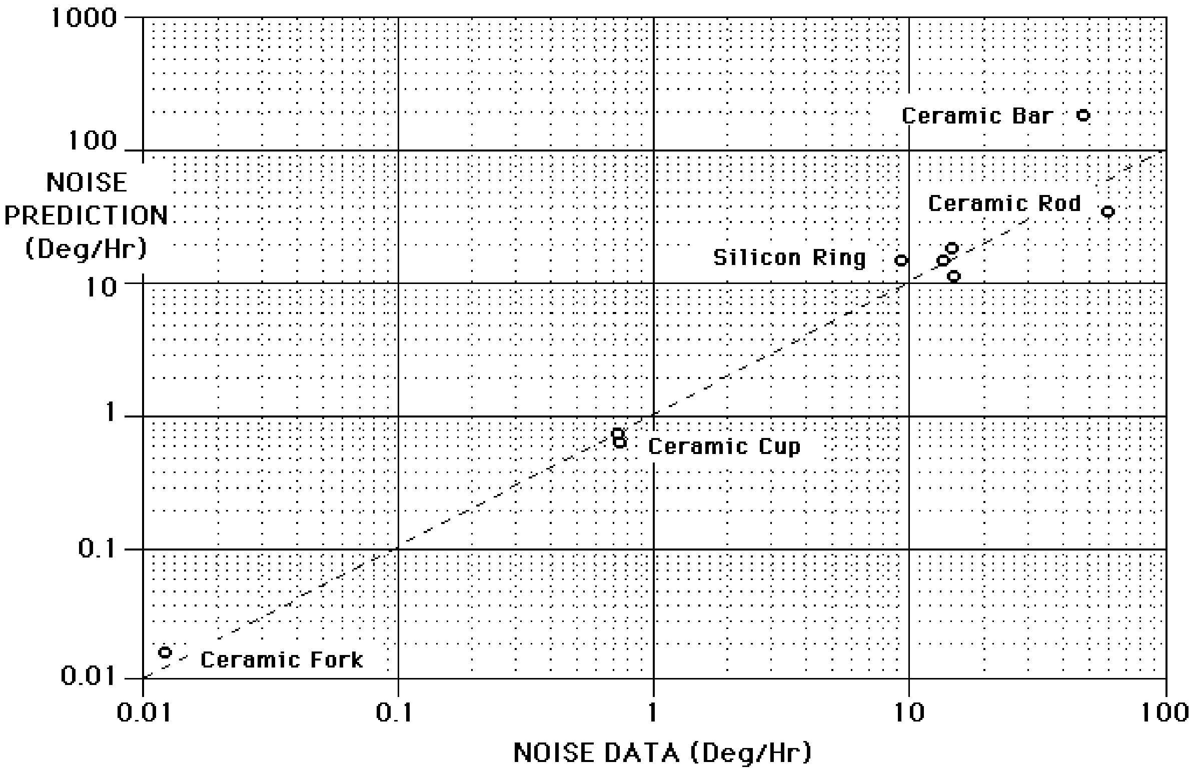

Figure 10. Comparison of Predicted to Tested Bias Noise

It is genuinely surprising that the correlation of the data from this formula to the test data is so strong. Instinctively the quality of the build process and the quality of the circuitry would seem to have enough effect to somewhat randomize the results. However, the nature of the gyros seems to dominate the results.

Conclusions and Recommendations

This formula says that if the size of a solid-state gyro is increased without changing frequency or Q, vast improvements in performance, at the sixth power of size change, can be achieved.

While this formula is interesting and potentially useful, an empirical formula for predicting bias noise is only a starting point for a theoretical study of gyro performance.

References

[1] W. S. Watson, Vibrating Element Angular Rate Sensor For Precision Applications, IEEE Position Location and Navigation Symposium, 1990.

[2] D.D. Lynch, Coriolis Vibratory Gyros, Symposium Gyro Technology, Stuttgart Germany, September 1998.

[3] C. Fell, I. Hopkin, K. Townsend, A Second Generation Silicon Ring Gyroscope, Symposium Gyro Technology, Stuttgart Germany, September 1999.

[4] Jason J. Ford, Michael E. Evans, On-Line Estimation of Allan Variance Parameters, Defense Science Technology Organization, Weapons Systems Division, P. O. Box 1500, Salisbury SA, 5108, Australia.

[5] W. S. Watson, Vibrating Structure Gyro Performance Improvements, Symposium Gyro Technology, Stuttgart Germany, September 2000.