Gyro Mechanical Performance: The Most Important Parameter

by Harvey Weinberg, Applications Engineering Group Leader, MEMS/Sensors Technology Group, Analog Devices, Inc.

IDEA IN BRIEF

It makes sense to select a gyroscope basesd on minimization of the largest error sources—in most applications, that will be vibration sensitivity. Other parameters can be easily enhanced via calibration or averaging multiple sensors. Bias stability is one of the smaller components of the error budget.

When looking over a high performance gyro data sheet the first thing most system designers look for is the bias stability spec. After all, this is what describes the resolution floor of the gyro, so it must surely be the best predictor of gyro performance! However, gyros in the real world exhibit errors due to multiple sources that prevent users from exploiting the high bias stability being touted in the data sheet. Indeed, about the only place you'll get that level of performance is on the lab bench. The classical approach is to add compensation to minimize the effect of these error sources. This article will discuss several of these techniques and their limitations. Finally, we will discuss an alternative paradigm—selecting a gyro for mechanical performance, and how to improve its bias stability, if necessary.

Environmental Errors

All low and moderate cost MEMS gyros exhibit some time-zero null bias and scale factor errors, as well as some variation over temperature. Therefore, it is common practice for users to temperature compensate them. Generally speaking, gyros contain integrated temperature sensors just for this purpose. Absolute accuracy of the temperature sensor is unimportant for this task—only repeatability and close coupling of the temperature sensor to the actual gyro temperature counts. Modern gyros' temperature sensors almost never have any trouble meeting these requirements.

There are many techniques that can be used for temperature compensation (polynomial curve fit, piecewise linear approximation, etc.). The particular technique used is of little importance as long as an adequate number of temperature points are recorded and sufficient care is taken during calibration. For example, insufficient soak time at each temperature is a common error source. However, no matter which technique is used or how much care is exercised, the limiting factor will be temperature hysteresis—that is, the difference in output at a specific temperature when that temperature is approached via cooling versus heating.

Figure 1 shows the temperature hysteresis loop of an ADXRS453 gyro. Null bias measurement of an uncompensated gyro was recorded while temperature was varied from +25°C, to +130°C, to −45°C, back to +25°C. There is a small difference in the null bias output at +25°C between the heating cycle and cooling cycle (in this case, about 0.2°/s)—this is temperature hysteresis. This error cannot be compensated out as it happens whether the gyro is powered or not. Furthermore, the magnitude of hysteresis varies proportionally to the amount of temperature "excitation" applied. That is, more hysteresis occurs when a greater range of temperature is applied to the device.

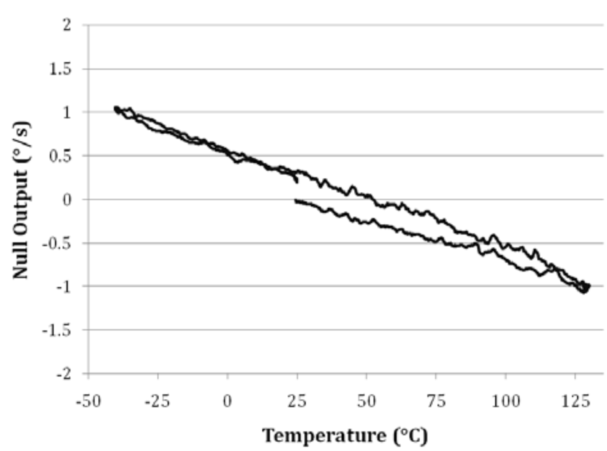

Figure 1. An Uncompensated ADXRS453 Null Bias Output While Being Cycled Over Temperature (−45°C to +130°C)

If the application allows for a reset of the null bias at turn-on (i.e., turn-on occurs when there is no rotation) or an in-field zeroing of the null bias, this error can be ignored. If not, this can be a bias stability performance limiter since one cannot control shipping or storage conditions.

Vibration Rejection

Ideally a gyro would measure only rotational rate, and nothing else. In practice, all gyros have some sensitivity to acceleration due to asymmetry of their mechanical designs and/or micromachining inaccuracies. In fact, there are multiple manifestations of acceleration sensitivity, the severities of which vary from design to design. The most significant are usually sensitivity to linear acceleration (or *g* sensitivity) and vibration rectification (or g^2 sensitivity). Since most gyro applications are in devices that move about and/or rotate through the Earth's 1 *g* field of gravity, sensitivity to acceleration often represents the largest error source.

Very low cost gyros are generally designed using extremely simple and compact mechanical systems that are not optimized for vibration rejection (rather, they are optimized for low cost) and can suffer greatly due to vibration. Over 1000°/h/*g* (or 0.3°/s/*g*) of *g* sensitivity or more is not unheard of—more than 10 times worse than what one would expect from a high performance gyro! There is little point looking for good bias stability in such a gyro, as small rotations of the gyro through the Earth's field of gravity will result in huge errors due to *g* and g^2 sensitivity. Generally, vibration sensitivity is not specified in these types of gyros—it is assumed to be very large.

Higher performance MEMS gyros fare much better. Table 1 shows the data sheet specifications for several high performance MEMS gyros. Most gyros in this class display *g* sensitivity of 360°/h/*g* (or 0.1°/s/*g*) and some under 60°/h/*g*. Much better than very low cost gyros, but even the best of these still exceed their specified bias stability when subjected to acceleration changes of as little as 150 m*g* (the equivalent of 8.6° of tilt).

Some designers attempt to compensate for g sensitivity using an external accelerometer (this is most often done in IMU applications as the requisite accelerometer is already present), and this can indeed improve performance in some cases. However, *g* sensitivity compensation cannot be entirely successful for a number of reasons. Most gyros tend to have *g* sensitivity that varies due to frequency of vibration. Figure 2 shows the response of a Silicon Sensing CRG20-01 gyro due to vibration. Note that while the gyro's g sensitivity is within its rated specifications (with the exception of some minor spurs at particular frequencies—but these are not likely important), it does vary over a ratio of 12 to 1 from dc to 100 Hz, so calibration cannot be done by simply measuring g sensitivity at dc. Indeed, a compensation scheme would be very complex requiring varying sensitivity with frequency.

Table 1.

Manufacturer	Part Number	*g* Sensitivity (°/s/*g*)	g^2 Sensitivity (°/s/g^2)	Bias Stability (°/h)
Analog Devices	ADXRS646	0.015	0.0001	8
Melexis	MLX90609	0.1	Not Specified	17
Silicon Sensing	CRG20-01	0.1	0.005	5
VTI	SCR1100-D04	0.1	Not Specified	2.1

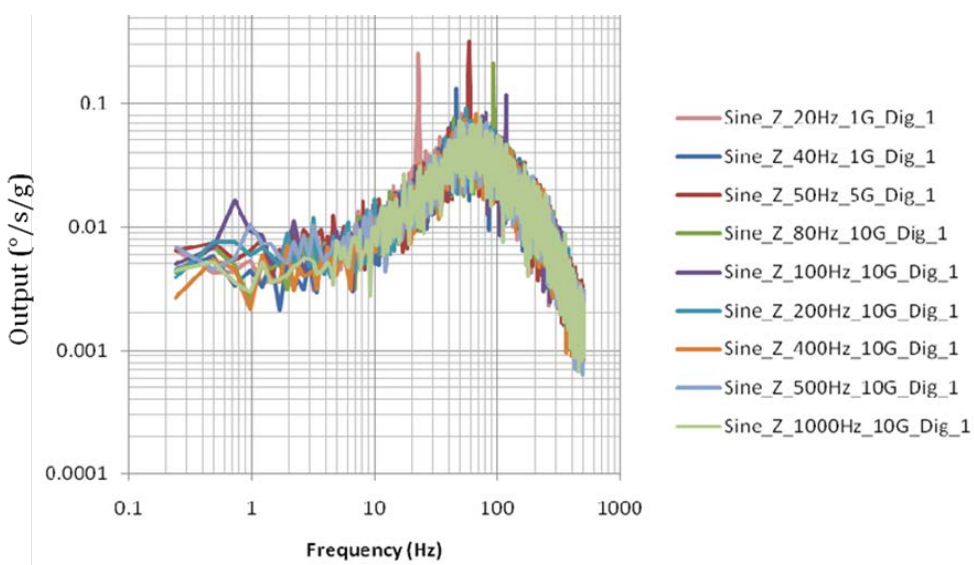

Figure 2. Silicon Sensing CRG20-01 g Sensitivity Response to Various Sine Tones

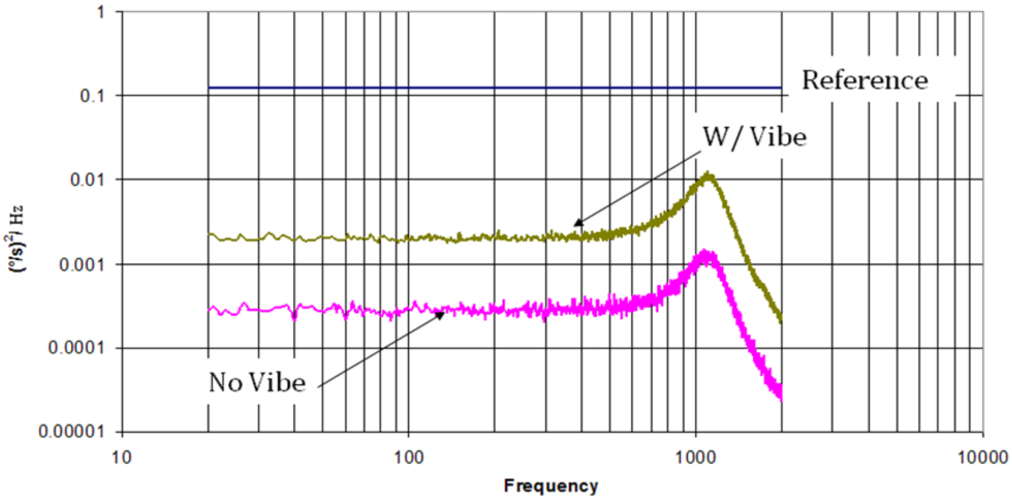

Figure 3. Analog Devices ADXRS646 g Sensitivity Response to Random Vibration (15 g rms, 0.11 g^2/Hz) 1600 Hz Filtered

In contrast, Figure 3 displays the response of the ADXRS646 gyro under similar conditions. The take-away is that some gyros are easier than others to *g* sensitivity compensate. Sadly, this information is almost never available in data sheets and must be discovered—possibly at great pain—by the user, often during system design where there is no time for surprises.

Another difficulty lies in matching the phase response of the compensating accelerometer with the gyro. If the phase response of the gyro and compensating accelerometer are not well matched, high frequency vibration errors might actually be magnified! Leading us to another conclusion: *g* sensitivity compensation only works at low frequencies for most gyros.

Vibration rectification is often left unspecified. Sometimes this is because it is embarrassingly poor or varies greatly from device to device. At times it is merely due to a gyro manufacturer's unwillingness to test or specify it (to be fair, it can be hard to test). Either way, vibration rectification should be of concern, as it cannot be compensated for with an accelerometer. Unlike the accelerometer's response, the gyro's output error is rectified.

The most common strategy to improve g^2 sensitivity is to add a mechanical anti-vibration mount as seen in Figure 4. Shown is a Panasonic automotive gyro partially removed from its metal-can package. The gyro assembly is isolated from the metal can with a rubber anti-vibration mount. Anti-vibration mounts are very difficult to engineer as they do not have flat response over a wide frequency range (they work particularly poorly at low frequencies) and their vibration reduction characteristics change over temperature and life. Indeed, as with *g* sensitivity, the gyro's vibration rectification response may vary over frequency. While anti-vibration mounts can be successfully engineered to attenuate narrow-band vibration in a known spectrum, such mounts are problematic for any general-purpose application where wide band vibration might be present.

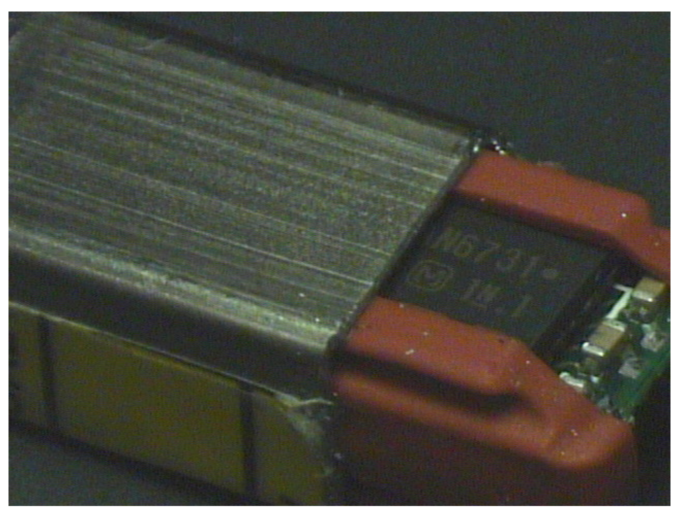

Figure 4. A Typical Anti-Vibration Mount

Major Misbehavior Due to Mechanical Abuse

Many applications routinely have short term abuse events that, while not damaging to the gyro, produce large errors. Presentation of a few examples follows.

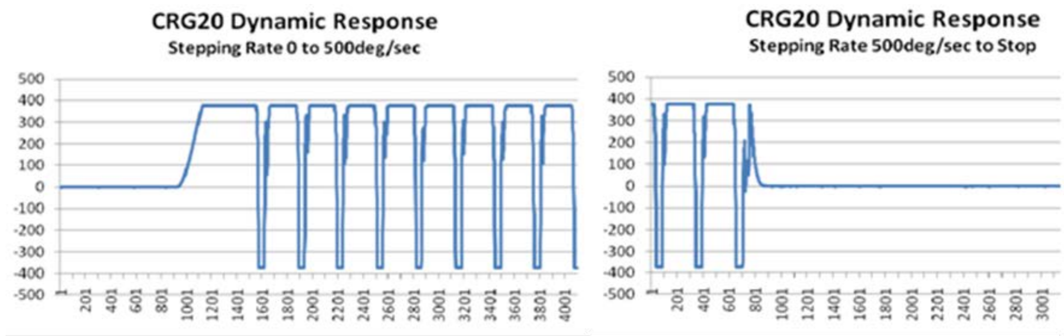

Figure 5. Silicon Sensing CRG-20 Response to 500°/s Rate Input

Some gyros cannot tolerate rate overload without misbehavior. Figure 5 shows the response of a Silicon Sensing CRG20 gyro to rate input approximately 70% over the specified range. The curve on the left shows the CRS20's response when the gyro is subjected to rotation from 0°/s to 500°/s and sustained. The curve on the right shows it's response when the input rate is reduced from 500°/s to 0°/s. The output swings wildly from rail to rail when the rate input is beyond the rated measurement range.

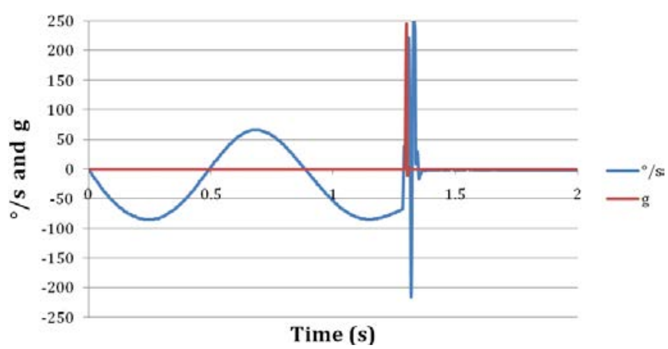

Figure 6. VTI SCR1100-D04 Response to 250 g, 0.5 ms Shock

Other gyros have a tendency to "lock up" when exposed to shocks as small as a few hundred *g*. For example, Figure 6 shows the response of a VTI SCR1100-D04 when subjected to a 250 *g* 0.5 ms shock (generated by dropping a 5 mm steel ball on the PCB next to the gyro from a distance of 40 cm). The gyro is not damaged by the shock, but it no longer responds to rate and needs to be power cycled to restart. This is not highly unusual; several gyros exhibit similar behavior. One would be wise to check if a gyro under consideration can tolerate the shock in your application.

Clearly errors of this type would be grossly large. So care must be exercised in determining what abuse conditions might be present in any given application and verifying that the gyro can tolerate those conditions.

Error Budget Calculation

As mentioned earlier, most gyro applications are in situations where movement or vibration is present. Typical error budgets for the gyros shown in Table 1 used in various applications are shown in Table 2 using the data sheet specifications shown previously (in cases where vibration rectification is not specified, a conservative estimate was used). As can be seen in Table 3, the addition of a *g* sensitivity compensation scheme that improves vibration performance by half an order of magnitude (no easy task) still results in vibration sensitivity often being a much larger error contributor than bias stability.

Table 2. Estimated Error (°/s) Due to Vibration for Several Gyros (Uncompensated)

Manufacturer	Part Number	Running (2 *g* Peaks)	Helicopter (0.4 *g* Vibration)	Shipboard (0.5 *g* Listing)	Construction Equipment (50 *g* Peaks)
Analog Devices	ADXRS646	4	22	5	36
Melexis	MLX90609	35	150	38	1080
Silicon Sensing	CRG20-01	32	147	37	630
VTI	SCR1100-D04	35	150	38	1080

Table 3. Estimated Error (°/s) Due to Vibration for Several Gyros with *g* Sensitivity Compensation (*g* Sensitivity Improved by Factor of 5)

Manufacturer	Part Number	Running (2 *g* Peaks)	Helicopter (0.4 *g* Vibration)	Shipboard (0.5 *g* listing)	Construction Equipment (50 *g* Peaks)
Analog Devices	ADXRS646	1	4	1	14
Melexis	MLX90609	12	35	9	936
Silicon Sensing	CRG20-01	9	32	8	486
VTI	SCR1100-D04	12	35	9	936

A New Selection Paradigm

Since bias stability is one of the smaller components of error budget, it is more sensible to select a gyro based on its minimization of the largest error sources—in most applications, that will be vibration sensitivity. However, sometimes you may still want lower noise or better bias stability than your selected gyro offers. Fortunately, there is a solution: averaging.

Unlike environmental or vibration errors that are design driven, bias stability error of most gyros has the property of noise. That is, uncorrelated from device to device. Therefore, one can improve bias stability performance by averaging multiple devices. For every n devices averaged, an improvement of $\sqrt{n}$ can be expected. Broadband noise may also be similarly improved by averaging multiple gyros.

Conclusion

While bias stability has been long considered the "gold standard" specification for gyros, in the real world, vibration sensitivity is often the more severe performance limitation. Selection of a gyro based on its vibration rejection capabilities is sensible as other parameters can be easily enhanced via calibration or averaging multiple sensors.

Appendix: Calculating Error Due to Vibration

Calculating the error due to vibration in any given application requires some knowledge of the magnitude of acceleration one can expect, as well as how often such acceleration may occur. The applications described in Table 2 and Table 3 break down as follows:

- Running typically generates peaks of 2 *g* for about 4% of the time.
- Helicopter vibration is fairly constant. Most helicopter specifications call for 0.4 *g* broad spectrum vibration for 100% duty cycle.
- Ships in rough water—particularly small craft—can list ±30° (generating ±0.5 *g*). Duty cycle can be assumed to be 20%.
- Construction equipment, like graders or front-end loaders, generates high-*g* (50 *g*) low duration shock whenever their blade/bucket strikes rock. A 1% duty cycle is typical.

To calculate error due to vibration, *g* sensitivity as well as g^2 sensitivity must be considered. So for a helicopter application, for example:

$$\text{Error} = [\,g \text{ sensitivity error}] + [\,g^2 \text{ sensitivity error}]$$
$$= [0.4\,g \times g \text{ sensitivity} \times 3600 \text{ s/h} \times 100\%] +$$
$$[(0.4\,g)^2 \times g^2 \text{ sensitivity} \times 3600 \text{ s/h} \times 100\%]$$

If *g* sensitivity is compensated via an accelerometer, only the *g* sensitivity is reduced by the compensation factor.

RESOURCES

To learn more about gyroscopes, MEMS, and inertial sensing solutions, visit www.analog.com/MEMS.

Products Mentioned in This Article

Product	Description
ADXRS646	High Stability, Low Noise Vibration Rejecting Yaw Rate Gyro

One Technology Way • P.O. Box 9106 • Norwood, MA 02062-9106, U.S.A.
Tel: 781.329.4700 • Fax: 781.461.3113 • www.analog.com

T09829-0-9/11(0)