Common Design Techniques for BEI GyroChip* Quartz Rate Sensors for Both Automotive and Aerospace/Defense Markets

Asad M. Madni, Fellow, IEEE, Lynn E. Costlow, Member, IEEE, and Stuart J. Knowles

Abstract—In the early 1990s, Systron Donner Inertial Division (SDID), a subsidiary of BEI Technologies, Inc., possessed a new solid-state rate gyroscope technology that had not yet matured or captured a significant market share. Even though some success had been achieved in defense missile applications, a strategy was clearly needed to further develop the technology and lay the foundation for future growth. The strategy search led to discovery of a leading edge automotive brake system application, which, in turn, led to a radical change in design and manufacturing approaches, as well as a dramatic increase in revenues. The resultant radical cost-reduction of quartz rate sensor (QRS) components has benefit for both the automotive and the aerospace and defense (A&D) applications. Commonality of design and design techniques is leveraging high-volume, low-cost automotive components into low-volume A&D products.

Index Terms—GyroChip, microelectromechanical systems (MEMS) gyroscope, quartz rate sensor (QRS), yaw sensor.

I. INTRODUCTION

In the first half of the 1990s, Systron Donner Inertial Division (SDID) concentrated on the aerospace and defense (A&D) market, a focus unbroken in over 40 years. The company was well established in low-volume, highly engineered special inertial sensor products. These products were typically extremely high performance, one-of-a-kind designs which solved challenging inertial problems for ships, aircraft, missiles, launch vehicles, and spacecraft (see Fig. 1). As the government delayed or cancelled production programs during those years, revenues fell by nearly one-half. This decline was driven by reduced demand for SDID’s older inertial product line and only a limited market penetration by the new quartz rate sensor (QRS) technology.

The QRS exhibited promise for manufacturing with high-volume methods. However, the low production volume demand before 1995 could not justify the capital expense to automate the low-volume, labor-intensive manufacturing methods. A growth strategy was clearly needed to take advantage of the promise of the QRS [1].

This paper describes the cost reduction methodologies, reliability implications, and automotive market penetration of the BEI Technologies, Inc., QRS. An additional description is provided on leveraging automotive products into the aerospace/defense market by utilizing commonality of designs between the two market segments.

II. OVERVIEW OF QUARTZ RATE SENSOR CONCEPT

The QRS operates on the Coriolis effect principle [2] that converts momentum of a vibrating object into a force proportional to the angular rate of the plane of vibration. The vibrating object is a double-ended tuning fork micromachined from a single mono-crystalline piece of piezoelectric quartz. The piezoelectric property of the quartz converts the Coriolis forces into electrical charge signals proportional to angular rate. This conversion of angular rate to electrical charge is accomplished with a double-ended tuning fork featuring a pair of “drive tines” and a pair of “pickup tines” (see Fig. 2). The vibration motion is created by connecting the drive tines to an oscillator circuit, forming a classic crystal oscillator function. Oscillator frequency is constant at about 10 kHz and is set by the fundamental resonant mode of the quartz drive tines. Oscillator amplitude is regulated to a constant value by an automatic gain control (AGC) loop in the oscillator circuit. When rotated about the sensing axis, the Coriolis effect creates a force vector \( \vec{F} \) in the drive tines approximated by the following equation:

\[
\vec{F} \approx 2 \pi \omega_1 \times \vec{V}_r
\]  

where \( m \) is tine mass, \( \omega_1 \) is input angular rate vector in the sensing axis, and \( \vec{V}_r \) is instantaneous tine radial velocity vector. The force vector resists changes in the plane of vibration and is proportional to the rate of change of the plane of vibration. Thus, the Coriolis effect reminds us of the principle of conservation of linear momentum, where objects with mass require external force to change their momentum vector.

As the drive tines attempt to maintain the original vibration plane during rotation, they exhibit a component of vibrating motion at 90° with respect to their original plane of vibration. When a drive tine moves away from the fork plane in one direction perpendicular to the fork plane, the other drive tine moves in an equal and opposite direction. This Coriolis motion is mechanically coupled to the pickup tines through the center section of the tuning fork. The pickup tines then vibrate similarly at an amplitude proportionate to angular rate. The pickup tine motion...
generates mechanical stress in the tine, which in turn generates an electrical charge due to the piezoelectric effect. Pickup tine electrodes collect the charge and signal conditioning electronics amplify the 10 kHz charge signal. Subsequent signal processing converts the signal amplitude to dc. The amplitude of the dc rate sensor output is proportionate to the angular rate magnitude and its polarity indicates direction of the angular rate [3]. See Fig. 2.

The QRS and signal conditioning electronics response to angular rate input may be viewed as an “AM radio” with a 10-kHz carrier signal with information carried in the sidebands caused by the modulation of the carrier due to the input rate signal. The information is extracted by conversion to base band (near dc) by synchronous demodulation and low pass filtering.

III. AUTOMOTIVE STABILITY CONTROL OPPORTUNITY

In researching new markets in 1992, the company identified an automotive brake system application that required inertial angular rate sensing. Since gyroscopes had never been engineered and adapted to automotive service, the application represented an emerging market. “Vehicle stability control” (VSC) systems measure the vehicle yawing (turning) rate and a brake computer compares it to the desired yaw rate from the driver steering wheel command. A skid situation is detected by an out-of-tolerance comparison in an algorithm which causes a momentary automatic application of either left or right brake(s) to correct or “stabilize” the vehicle. VSC systems enhance the safety of traditional antilock brake systems (ABSs) for a relatively small increase in cost [4], [5]. This automotive application requires a gyroscope with extreme reliability, medium performance, very low unit cost, built-in-test capability and high-volume manufacturability. The QRS concept successfully met all of these requirements.

The QRS met initial automotive cost targets by the automotive industry and captured a significant fraction of the world market. On-going cost reduction efforts are necessary to remain competitive in an industry that expects year-on-year price decreases. Current BEI product offerings include the roll stability control sensor cluster with two gyros, two accelerometers, power conditioning and a digital controller area network bus (CANbus) interface in a single package for a “two digit” price which is less than the original single QRS gyro yaw rate Sensor in 1996.

A. Cost Reduction Methodologies

Prior to the automotive market thrust, SDID manufacturing processes and QRS designs were inefficient, labor-intensive, and not amenable to high-volume techniques. Consequently, unit costs were unacceptable in the automotive market. The QRS technology (now called the BEI GyroChip) had already met key performance characteristics that were orders of magnitude better than the automotive application. SDID’s A&D gyroscopes were focused on microminiature inertial measurement units (IMUs) and other high performance solid-state rate gyro applications [6]. The critical performance parameter is typically offset bias over temperature. Both aerospace product types vastly exceeded the automotive requirement as indicated by Table I.

1) High-Volume Manufacturability: The automotive challenge hinged on reducing the unit cost of the GyroChip concept to “double-digit” dollars from the three and four-digit levels common to A&D products. The cost reduction occurred primarily through selective investments in automation and significant advances in design techniques. In addition, advances were made in mass production techniques that were not previously employed by SDID. In making these changes, the performance was relaxed to the medium levels appropriate for automotive stability control [7].

Plastic injection-molding packaging designs were adopted providing near zero assembly labor and extremely high quality
resulting in high acceptance by the automotive industry (see Fig. 3).

2) More Forks Per Wafer: The classic semiconductor industry technique of more chips per silicon wafer was embraced by progressively moving from one tuning fork per quartz wafer to two, four, eight, 16, 30, and 56. All these designs utilized the same size wafer. This batch manufacturing radically reduced the cost per tuning fork as illustrated in Fig. 4. Performance degradation caused by automotive fork size reduction was avoided or significantly mitigated. Advanced automotive tuning fork designs actually improved performance despite significant reductions in fork size.

3) New Automation Techniques: Laser trimming of tuning fork parameters and gyro final assembly electrically programmable (EP) calibration techniques were employed to remove human labor, reduce cycle time, and add consistency of these critical steps. Continuous improvement of the laser trim cycle has optimized that process to maximize equipment capacity and throughput (see Fig. 5).

B. Reliability and Safety Characteristics

Success in the automotive market depended on a demanding combination of high reliability and the ability to self-detect gyro failures continuously during operation.

1) Extremely High Reliability: Automotive applications demand sensors with a minimum life of ten years. The solid state GyroChip had achieved an enviable aerospace reliability track record. Several million-device flight hours in a Boeing 777 production application without a single failure testified to the promise for automotive reliability. The automotive industry requires rigorous qualification testing prior to production launch. The extensive testing occurred at three levels: component (such as tuning fork), sensor (in a complete package), and...
vehicle (in the actual brake system). After production launch, the subsequent automotive reliability demonstrated capability for near zero parts per million (PPM) levels after resolution of early reliability issues. See Fig. 6.

2) Self-Monitoring for Safety Critical Systems: Rate gyro-scope applications frequently occur in systems that create a dangerous situation if the gyro fails without the host system detecting that the rate-sensing device is providing faulty information. This is inherent in systems that feature large motions that, when uncontrolled, generate an unsafe situation. Automotive stability control brake systems generate direction-changing (yawing) brake commands independent of the driver. For this reason, this “safety system” may become an “unsafe system” if it erroneously activates the brakes.

Some sensors, such as the VTI Technologies, Inc., SCA600 series silicon accelerometers, commonly used in automotive stability control brake systems, may be commanded to enter a self-test mode, which will cause the output to go to a specific value. During this time, the unit is not responding to inertial inputs. Consequently, this “commanded self-test” must be activated during power-up, before the vehicle is moving. During subsequent vehicle travel, the sensor cannot detect that it has failed after the initial self-test pronounced the sensor healthy. Since the accelerometer application is not as critical as the rate gyro, this sensor is widely used in stability control systems. The GyroChip employs a patented continuous built-in-test (CBIT) technique which monitors end-to-end fork and electronics sensor health continuously during operation [8]. CBIT is a

<table>
<thead>
<tr>
<th>FORK MODEL</th>
<th>FS3</th>
<th>FS2</th>
<th>625</th>
<th>STD4</th>
<th>STD8</th>
<th>272</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fork Length (Inches)</td>
<td>1.12</td>
<td>1.04</td>
<td>0.65</td>
<td>0.62</td>
<td>0.44</td>
<td>0.32</td>
</tr>
<tr>
<td>Automotive Application</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>Yaw</td>
<td>Yaw/Roll</td>
<td>Yaw/Roll</td>
</tr>
<tr>
<td>A&amp;D Application</td>
<td>Hi-Performance Rate</td>
<td>IMU</td>
<td>Hi-Performance IMU</td>
<td>Rate &amp; Low-Cost IMU</td>
<td>Rate</td>
<td></td>
</tr>
<tr>
<td>Automated Laser Trim</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
</tbody>
</table>

Fig. 9. STD4 fork.

Fig. 10. STD8 fork.

Fig. 11. Facets in an STD 4.

Fig. 12. Facets in an STD 8.

Fig. 13. Relative stress versus position along tine.
major contributor to stability control brake system safety. See Fig. 7.

C. Market Penetration

A combination of internal BEI factors and capabilities coupled with external world automotive events converged to provide dramatic market penetration and rapid growth to several million QRS shipments per year. By late 2003, BEI had shipped over seven million automotive units.

1) Initial Penetration Into Automotive Stability Control: In the 1993–1995 timeframe, SDID recognized the potential for the stability control expansion of ABS brake systems that required a rate gyroscope sensor. The company had already achieved contracts as the leading edge solid-state gyroscope supplier that offered the best combination of performance, cost, and reliability for the automotive application. Market growth rates and SDID market penetration were anticipated to exceed 20 to 30 % per year. The first production GyroChip yaw rate sensor shipped in June 1996 for application in the Cadillac StabiliTrak brake systems.

2) “Elk Maneuver” Creates Instant Demand: An unexpected event in the fall of 1997 determined that the market would mushroom, initially in Europe, at rates that were multiples of 100 % per year. The unforeseen event was the loss of control and rollover of a new European vehicle by a Swedish automobile magazine editor while executing a maneuver to simulate avoidance of an animal, such as an elk, crossing the road. At normal speed and good road surface conditions, the vehicle failed the maneuver and rolled over, creating a firestorm of adverse publicity in the automotive world.

In reaction to the “Elk Maneuver” episode, the manufacturer committed to fit all future vehicles with stability control. European competitors seized on a marketing opportunity and decided to significantly ramp up their offerings of stability control systems as well. Some even committed to make the feature available on all models of their product line. GyroChip demand skyrocketed by a factor of 10 to over 400 000 in the first full year of production for Europe (see Fig. 8).

The initial ramp-up has been followed by tremendous production growth through 2001. Customers have accepted the GyroChip in the U.S., Europe, and Japan, and the technology has penetrated the large truck/trailer stability control and SUV stability/rollover prevention markets.

IV. COMMON DESIGNS FOR AUTOMOTIVE AND A&D

A significant commonality of designs as well as manufacturing/test techniques has been achieved to maximize the leverage between the high volume automotive market and the lower volume A&D market. Common designs include quartz tuning forks, tuning fork packaging, application specific integrated circuit (ASIC)-based signal conditioning electronics, and sensor continuous (real-time) self-monitoring. Common manufacturing/testing techniques include tuning fork laser trimming, electronic sensor calibration programming, high volume temperature testing techniques, and SQL Server\(^1\) database SPC tools. Designs have capitalized on an intense on-going program to shrink the tuning fork sensing element using finite element analysis (FEA) techniques to dramatically reduce unit cost, while maintaining and even improving performance.

A. Common Tuning Fork Designs

FEA techniques are used to design tuning forks that achieve higher performance levels with smaller size. Smaller forks are, therefore, useful in A&D as well as automotive applications. Table II illustrates the overlap of fork size and market application for the QRS technology.

B. Hammerhead Tuning Fork Design Advantages

The STD4 model automotive tuning fork was launched in 1996 in the first automotive GyroChip. This fork featured square cross section tines and virtually all of its geometry featured 90° angles. It was fabricated using a quartz wafer layout of two rows of eight forks each (16 total forks per wafer). See Fig. 9. Soon work commenced on a second-generation automotive fork, called the STD8, that would meet more stringent design goals including:

- smaller size (more forks per wafer);
- lower cost;
- 120° versus 90° geometry features;
- pickup mode nodal line positioned at the center point mount;
- higher sensitivity;
- improved bias performance;

\(^1\)SQL Server is a registered trademark of Microsoft Corporation.
10–22 kHz fork drive frequency for production ASIC compatibility.

In addition, the STD8 was designed to retain the benefits of the center point mount concept (see Fig. 10).

Lower Cost—The STD8 achieved significant cost reduction for several reasons including more forks per wafer, lower process time in etch, and higher performance resulting in higher yields at GyroChip final test.

Center Mount—As with the STD4, the STD8 featured a single point center mount which guaranteed that no thermal expansion stresses could affect fork operation/performance due to differences in mount material and quartz [9].

Pickup Mode Nodal Line at Mount—A significant advance was achieved by a design that positioned the resonant pickup mode nodal line at the center point mount as opposed to above or below it. When the pickup mode nodal line is not at center point mount, external vibration will couple into the fork in a twisting manner that may appear to be Coriolis effect pickup tine motion. However, when the pickup mode nodal line is at the center point mount, the vibration will appear as a “common mode” motion and be rejected (not interpreted as a pickup signal).

No Square Inside Angles—The hammerhead fork design avoids square (90°) geometry features on inside angles throughout the design in favor of 120° angles. This geometry results in a much more “quartz wet etch friendly” design. By taking advantage of the fact that quartz etches at different rates in different axes due to orientation of the crystalline structure, the 120° geometry avoids the undesired “webs” or “facets” at inside angles after the etch process (see Figs. 11 and 12). Since facets degrade fork performance due to unintended material remaining in the fork, this approach improves fork performance [10].

Tapered Tines—A striking feature of the hammerhead fork is the tapered tines topped with larger masses (hammerheads) as opposed to the straight tines of the STD4 fork. The taper, in conjunction with the masses, distributes stress in both the drive and pickup tines in a constant manner along the tine length. In contrast, the square tines generate stress that is highly localized at the base of the tine, making piezoelectric charge generation and electrode collection of the charge less effective. The difference in stress distribution between the two designs is highlighted in the graph in Fig. 13. In addition, FEA pictures in Fig. 14(a) and (b) illustrate the concentrated stress at the tine base in the square STD4 fork and the uniformly spread stress in the tapered tine STD8 fork.

Hammerhead Masses—The unusual masses at the end of the tapered tines add momentum, a key factor in generating more Coriolis force for a given length of fork. The masses also allow the fork frequency to be reduced, which would be excessively high with just tine tapering alone. All forks operate in the 10–17 kHz frequency region. Higher frequencies would require redesigned ASIC signal conditioning electronics with higher bandwidth amplifiers.

The tapered tine/hammerhead design offers higher sensitivity with a smaller fork size, a result opposite to that expected with a fork size reduction. This improvement is the result of both better drive behavior, and enhanced pickup coupling. The drive system has a higher “Q,” due to reduced tine displacement and improved charge coupling of the tines. This lowers impedance allowing for higher drive current levels from a given voltage source, and decreases zero rate offset bias.

Finally, the tapered tine concept offers design control variables that include not only length and width (as with the square tine design), but also taper and hammerhead mass size. This additional design flexibility allows for more optimization of the overall structure, and eases challenges such as the pickup mode nodal line centering.

**C. Suitability of Automotive Forks for A&D**

A key reason automotive tuning forks find application in A&D products centers on the advances made in fork sensitivity, coupled with progressively smaller fork size. Major advances have been achieved in signal output with significantly smaller tuning forks. This has been attained through dramatic improvements in design. Higher signal levels make it possible to reduce undesirable errors including noise and offset (bias) accuracy/repeatability and generally make for a more robust gyro. Consequently, these quartz rate sensors meet the more stringent vehicle dynamic control yaw rate sensor specifications more robustly than other designs. Table III indicates absolute fork improvements in design. Higher signal levels make it possible to reduce undesirable errors including noise and offset (bias) accuracy/repeatability and generally make for a more robust gyro. Consequently, these quartz rate sensors meet the more stringent vehicle dynamic control yaw rate sensor specifications more robustly than other designs. Table III indicates absolute fork size (length) along with relative length and relative sensitivity for three different forks that are designed for the automotive market.

The stronger sensitivities with the newer, smaller (and lower cost) forks represent a major advancement in the robustness of quartz tuning fork design. The STD4 fork is in service in the Boeing 737 yaw damper control system. The STD8 is finding application in low-cost IMUs, attitude heading and reference systems (AHRGs), and has already entered low-rate initial production (LRIP) on the Predator Anti-Tank Weapon System. The 272 is expected to find application in certain G-hardened products such as munitions requiring components with massive shock immunity and moderate performance.

Fig. 15 depicts SDID’s highly automated fork packaging and laser trimming facility for automotive forks and the high performance 625 A&D fork.

**TABLE III**

<table>
<thead>
<tr>
<th>Fork Model</th>
<th>Year Available</th>
<th>Available Range(s) (deg/sec)</th>
<th>Typical Noise Floor (deg/sec/rt Hz)</th>
<th>Fork Length (Inches)</th>
<th>Relative Length (Percent)</th>
<th>Relative Sensitivity (Percent)</th>
<th>Figure of Merit (Relative Sensitivity/Relative Length)</th>
</tr>
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<tbody>
<tr>
<td>STD4</td>
<td>1996</td>
<td>±64, ±75</td>
<td>0.025</td>
<td>0.62</td>
<td>100</td>
<td>100</td>
<td>1.00</td>
</tr>
<tr>
<td>STD8</td>
<td>2000</td>
<td>±75, ±300</td>
<td>0.042</td>
<td>0.44</td>
<td>71</td>
<td>252</td>
<td>3.55</td>
</tr>
<tr>
<td>272</td>
<td>2002</td>
<td>±75, ±300</td>
<td>0.028</td>
<td>0.32</td>
<td>51</td>
<td>134</td>
<td>2.63</td>
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</tbody>
</table>
Fig. 15. Fork packaging (nugget) factory. (Right) Packaging line; (left) laser trim line.

Fig. 16. Bias plot (std. dev.) for STD8 fork.

D. Automotive Fork Applications in A&D Products

In the mid-1990s, as defense production decreased and automotive MEMS high volume rate sensor production increased, it became clear that significant A&D cost reduction was also possible. During this time, the government initiated the Commercial Technology Insertion Program (CTIP) to capture commercial technology and insert it into defense applications.

BEI, as part of an ongoing cost reduction activity, initiated a concept demonstration featuring the STD4 automotive fork for the Predator missile program that used a more expensive BEI quartz fork. The original fork was a STD4 quartz design, but was manually trimmed. In addition, it was packaged in a custom machined housing which was several times more expensive than the high volume stamped metal STD4 automotive housing. While the new design was first treated as a long term cost reduction, once tested in the severe shock environments of the missile, the newly designed CTIP units were clearly superior. The customer readily accepted the CTIP version and BEI QRS automotive technology and low-costs continue as the baseline today. In the last year, the design was requalified yet again with the newer STD8 automotive fork.

As the automotive sensors mature and performance continues to improve, these sensors are finding their way into more and more sophisticated applications. Current developments include multi-axis implementations with bias performance measured in degrees per hour rather than degrees per second (see bias plot in Fig. 16). These plots depict bias performance versus temperature of an existing design using the latest automotive sensors and
a newly developed analog ASIC. A well-known bias temperature compensation technique can be used to “model” the errors out of an “imperfect” sensor by a polynomial equation such as

Bias error compensation
\[ \text{Bias error compensation} = K_0(T_0)^0 + K_1(T-T_0)^1 + K_2(T-T_0)^2 + K_3(T-T_0)^3 \] (2)

where \( T_0 = +25^\circ C \), \( T \) = actual sensor temperature, and \( K_0, K_1, K_2, K_3 \) = compensation coefficients, unique to sensor.

The bias error compensation value is subtracted from sensor bias to provide a compensated bias output at any given temperature. If the bias data contains errors that vary with temperature erratically (more than the third order polynomial), then bias compensation will be less accurate and the compensated sensor will have a larger bias error. The data in Fig. 16 shows “modelability” of bias standard deviation to a level of 55/\( ^h \) (0.015/\( s \)) using a third order polynomial. This performance exceeds that of older automotive stability control rate sensors by a factor of 100:1 and enables future low-cost, high performance, sensors and systems.

Products nearing market release include the quartz dual axis rate sensor (QDARS) for missile seeker applications (Fig. 17) and the 6DOF microminiature quartz (MMQ) IMU (see Figs. 18 and 19). Both products offer multi-axis sensing with automotive tuning forks, and very small size and low-cost coupled with excellent bias performance. Modeled bias performance is in the 100/\( ^h \) to 200/\( ^h \) region over \(-40 \) to \(+85 \) C. Near term applications for these low-cost assemblies include small, unmanned aerial vehicles (UAVs) and missile seeker applications.

G-hardened munitions opportunities will emerge with the introduction of even smaller automotive sensing elements. BEI has provided gun-launched quartz rate sensors in the past where significant G levels (ranging from 10 000 to 30 000 Gs) for launch and balloting loads exist. The smallest automotive forks will enable the offering of low-cost, rugged sensors for a broad spectrum of A&D as well as commercial applications [11].

E. Signal Conditioning Electronics

A family of signal conditioning ASICs for tuning fork interface spans both automotive and A&D applications. Table IV illustrates the common use of several ASICs. All three of the automotive ASICs are useful in certain A&D applications. These applications are typically medium performance in systems such as antenna stabilization, seeker motion control and super low-cost AHRS. All of the aerospace and defense IMUs utilize BEI’s vibrating quartz accelerometers (VQAs) in three of the six inertial sensing axes.

F. Novel Production Calibration Technique

Temperature Offset Bias Requirements—Automotive brake stability control customers demand tight absolute offset bias limits as well as stringent temperature discontinuity limits (no excessive bias changes for temperature changes—“dV/dT”). In addition, some customers impose production limits on bias output shifts (called “zero rate bias drift velocity”) in an environment of extremely rapid temperature rates of change. An example of a bias drift velocity temperature specification is: zero rate bias drift velocity \(<=25^\circ C/s/min\), at \(\pm 2.5\) K/min of ambient temperature rate of change.

The objective is to preclude the brake system, under any temperature scenario, from erroneously activating the brakes by interpreting rate sensor temperature-induced bias changes as “true yaw rate.”

The rate sensor designer is faced not only with designing and testing for tight absolute bias, but controlling momentary bias shifts as temperature gradients affect the output, aggravated by rapid ambient temperature changes. These scenarios are “real world” in that some automotive rate sensor installations are in the worst possible passenger compartment locations for temperature stability. One automaker installed the rate sensor in a heating/air conditioning duct near the floor, right over the catalytic converter!

ASIC Temperature Compensation Architecture—Recent automotiveASIC architecture includes the built-in ability to calibrate GyroChips for excellent bias performance over temperature, including limits on temperature-induced bias drift velocity. The rate signal is analog end-to-end, from tuning fork to analog rate output. Accordingly, it has near infinite resolution. However, the temperature calibration signal is digitized. When the calibration signal is summed with the rate signal for bias compensation, the rate output signal exhibits excessive discontinuities (quantization effects) if the compensation transitions are large. The calibration technique not only achieves low absolute offset bias, but also controls excessive rate output discontinuities as temperature changes.

An A/D converter digitizes the on-chip temperature sensor. The digitized temperature forms an “address pointer” to memory locations that store calibration coefficients as a function of instantaneous temperature. Since the least significant bit (LSB) of the digitized temperature represents approximately 1.0 C, calibration coefficients are updated if the temperature

<table>
<thead>
<tr>
<th>ASIC</th>
<th>ASIC-1</th>
<th>ASIC-2</th>
<th>ASIC-3</th>
<th>C029</th>
<th>DCO</th>
<th>DIG</th>
<th>DFA</th>
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<tbody>
<tr>
<td>Type of Signal Processing</td>
<td>Analog</td>
<td>Analog/Digital Mixed Signal</td>
<td>Analog/ DSP</td>
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<td>Analog</td>
<td>DSP</td>
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<td>Automotive Application</td>
<td>Yaw/Roll</td>
<td>Automatic Cal Yaw/Roll</td>
<td>Automatic Cal Yaw/Roll</td>
<td>--</td>
<td>--</td>
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<tr>
<td>A&amp;D Application</td>
<td>Rate</td>
<td>Automatic Cal Rate</td>
<td>Automatic Cal Rate</td>
<td>Hi-Performance Rate</td>
<td>QRS Drive IMU</td>
<td>6DOF IMU</td>
<td>6DOF IMU</td>
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</tbody>
</table>
changes as little as 1.0 °C. Each calibration coefficient has a resolution of 0.1 °C/s of equivalent angular rate.

Calibration Technique Equipment—A novel technique that accomplishes calibration in high volume production with near-zero labor and fast cycle time has been developed which provides excellent zero rate offset bias performance over temperature. The automated calibration algorithm operates simultaneously on 256 units in a two-chamber “shuttle oven” that rapidly moves the units through two complete temperature cycles with extremes at −40 °C and +85 °C. One shuttle oven chamber is fixed at −40 °C and the other at +85 °C. The units “shuttle” through the temperature extremes of both chambers (ambient to hot to cold to ambient) and a test computer continuously monitors the output offset of all 256 units (see Fig. 20).

Calibration Temperature Cycle—During the first temperature cycle, the computer generates unique compensation coefficients for each unit and programs them into EEPROM locations in piecewise linear segments. Every 5 °C, a new coefficient is calculated and every 1 °C an EEPROM location in between these values is programmed with linearly interpolated values. A “coarse/fine” technique programs locations ahead of the current location with the same value as current location (a “coarse” calibration) and then a fine adjustment is made when the “next location” becomes a “current location.” At the completion of the temperature cycle loop, the array of EEPROM values is smoothed by performing a fifth order polynomial curve fit on the 26 data points (every 5 °C) using a least squares fit. The resulting polynomial has the form

\[ Y = X_0 T^0 + X_1 T^1 + X_2 T^2 + X_3 T^3 + X_4 T^4 + X_5 T^5 \]  

where \( Y \) is the desired EEPROM calibration value, \( T \) is digitized temperature used as EEPROM address pointer, and \( X_0, \ldots, X_5 \) are calibration constants.

The resulting polynomial equation is used to re-calculate new numbers for all EEPROM locations at each 1 °C. A unit with two adjacent EEPROM locations that differ more than a specified limit (an excessive discontinuity or “dV/dT”) is rejected at this point. The six calibration constants have limits imposed on them to prevent shipping a unit that has an excessively large uncalibrated bias versus temperature characteristic.

Calibration Verification Temperature Cycle—After the computer re-programs the EEPROM in each unit with its respective polynomial equation, the units are shuttled back through the temperature loop in a verification cycle. The offset bias of all units is measured against absolute specification and bias drift velocity limits to verify that final calibration successfully meets the bias specification.

Advantages of the calibration technique are:
- Extremely high bias offset accuracy for automotive stability control. Tight bias calibration coupled with stability of quartz provides 10–20 years of reliable bias performance (see Fig. 21) for a typical offset bias performance;
- Tight screening control over units with excessive uncalibrated behavior;
- Tight screening control over offset bias temperature discontinuities (“dV/dT”) that might be interpreted as a large automotive yaw rate by the brake computer;
- Calibration process robustness over large populations (see Fig. 22);
- Near zero labor to load/unload shuttle ovens, all else is computerized;
- Low calibration data storage (only six polynomial constants) for permanent record keeping of bias calibration data for every unit (millions of units/year);
- Requires only two temperature cycles—calibration and verification;
- Low cycle time for the shuttle ovens to “slam” the units toward temperature extremes at very fast rates. Each temperature cycle is 45 min.

V. CONCLUSION

QRS technology originated at SDID in the high performance A&D market and was successfully adapted to the demanding
high-volume, low-cost world of automotive production. Along the way, the BEI GyroChip played a key international role in launching next generation stability control brake systems.

By adapting automotive components, with their extremely low-costs, back into A&D applications, SIDID is leveraging the automotive technology into low-volume markets with high-volume/low-cost components. In those applications where the performance level is adequate, the low costs represent an extremely competitive advantage.

Newer automotive tuning fork and ASIC designs have improved the performance, while decreasing cost. Consequently, automotive components offer additional options for A&D market penetration.

A&D products now use other common techniques mastered in the automotive product lines. These include automated manufacturing such as sensing element laser trim, final assembly electronic programming calibration, high-volume calibration over temperature and SQL Server manufacturing database, and statistical process control tools.

Certain automotive design features may also benefit A&D products including safety-critical CBIT, analog/mixed signal/DSP ASIC designs, and graded performance techniques similar to those used by integrated circuit industry. Finally, BEI offers higher performance inertial packages including fully integrated IMU/GPS units (C-Migits) that utilize both the QRS and VQA.

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