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Advanced Triaxial Accelerometer for Race Car Performance Enhancement

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ABSTRACT

Motorsports recognizes the need for a triaxial accelerometer that can provide accurate vibration results in pre-race trials, and real-time measurements during the course of an actual race. Precise data needs to be gathered that allows the racing engineer to determine design modifications and suspension adjustments when fractions of a second can determine the winner.

Measurement Specialties, Inc. has developed the Model 4203 accelerometer that satisfies these requirements. The accelerometer features a silicon sensor element utilizing silicon MEMS technology (Micro Electro Mechanical Systems) packaged in a lightweight metal housing. DC capability allows the capture of long duration transients in order to measure whole body motion. On-board signal conditioning outputs high level, low impedance signals. Each of the full scale g-ranges of the three orthogonal axes can be independently selected for optimum measurement resolution.

INTRODUCTION

This paper describes the unique features of the sensor element, signal conditioning, and packaging of a triaxial accelerometer designed for the NASCAR, IRL, and Formula 1 racing teams. Presented are track results generated by a NASCAR racing team.

A bulk micromachined piezoresistive sensor element contains a four leg Wheatstone bridge. Temperature correction of performance shifts is accomplished using a digitally programmable IC with an on-board temperature sensor. A screw-mountable aluminum enclosure is low profile for ruggedness and improved aerodynamics. The device can be mounted in areas not usually accessible with larger, cube-shaped accelerometer designs.

The application requires the making of low level measurements in the presence of severe engine vibration. Extraneous signals are removed by a combination of a critically gas damped sensor element and a factory adjustable eighth-order low pass filter. The accelerometer incorporates EMI/RFI filtering. The shielded cable is ETFE jacketed with #24 AWG conductors for durability. The 4203 accelerometer is used for track mapping that establishes the optimal racing line for a given course. Bumps in the track are characterized for magnitude and direction. Acceleration and braking forces are examined, as well as vehicle flexing. These are factors that need to be controlled in order to avoid scrubbing off speed during a race. Figure 1 is a photograph of the Model 4203.

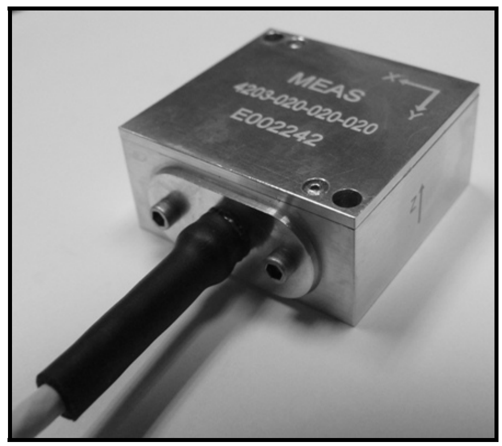

FIGURE 1 – MODEL 4203 TRIAX ACCELEROMETER

SENSOR ELEMENT

The open-bridge piezoresistive MEMS sensor element consists of a stack of three silicon layers bonded together. The sensor element is 0.134 inch square with a height of 0.05 inches (3.4 mm square by 1.3 mm). Figure 2 depicts the sensor with its top layer partially removed.

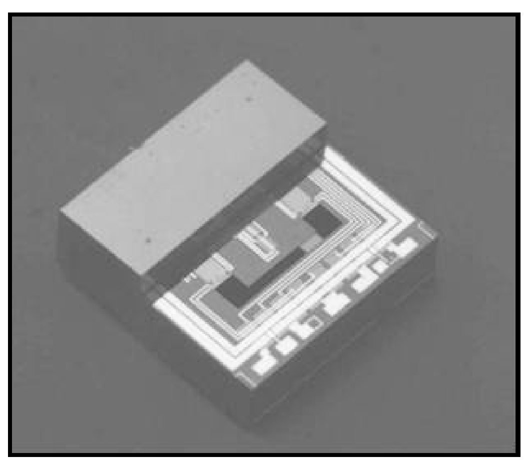

FIGURE 2 – PR SENSOR ELEMENT, UNCOVERED

Figure 3 is a cross-section of the sensor element. The middle layer contains the proofmass suspended from a frame by four beams, approximately 10 microns thick, in a double cantilever configuration. This arrangement provides rectilinear motion. The flexures include a thin web between each set of beams, 5 microns thick, that allows stiff lateral support. This feature constrains cross-axis movement of the proofmass from out-of-plane vibrations and shocks. The sensitivities of the sensor elements are adjusted for the various full scale ranges by changing the thickness of the beams and diaphragms.

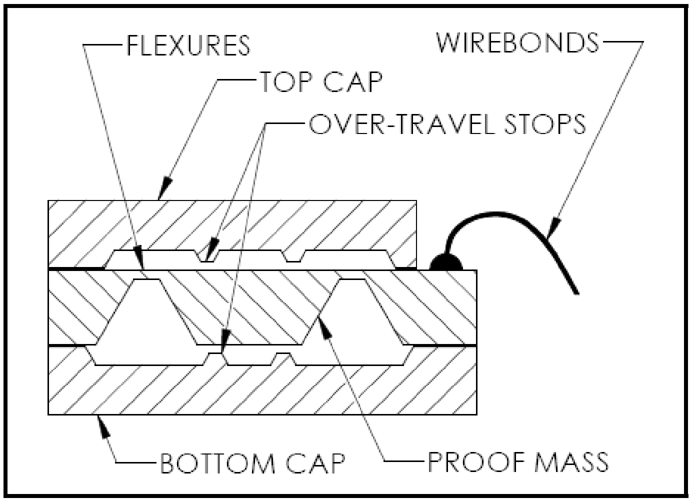

FIGURE 3 – SENSOR CROSS-SECTION

The middle layer is contained between a silicon top cap and a base cap that, along with the frame, form an enclosure around the proofmass. The caps provide squeeze-film gas damping that is nominally set to 0.7 critical. The etch depths of the cavities in the caps are important in determining damping. This mechanically suppresses resonant peaks.

Note that a gas damping medium is far superior to fluid damping when having to operate in temperatures beyond room ambient. Figure 4 shows the temperature dependence of the frequency response of a fluid damped accelerometer compared to that of gas damped.

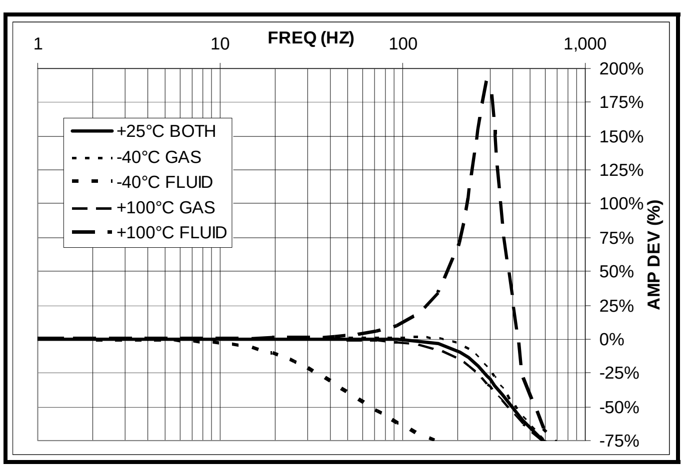

FIGURE 4 – DAMPING MEDIUM COMPARISON

The caps also contain over-travel stops that limit the motion of the proofmass so that it does not reach the point at which the flexures fracture. Figure 5 is a SEM photograph of a sectioned sensor that depicts 15 micron gaps between the proofmass and the outer caps. The over-travel stops within the gaps limit proofmass travel to approximately 5 microns.

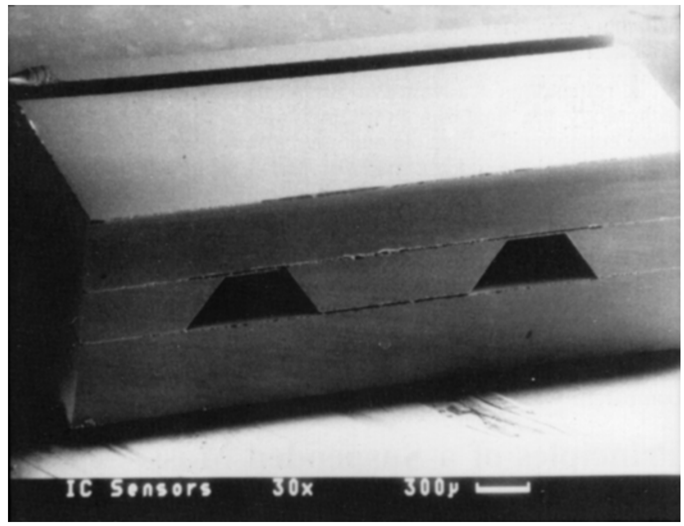

FIGURE 5 SECTIONED SENSOR ELEMENT

Single-crystal silicon does not experience fatigue failures. Stiction is prevented by minimizing the contact surface area of the faces of the over-travel stops with that of the proofmass. Stiction is a phenomenon in which the proofmass remains stuck to the over-travel stops when unable to overcome static cohesion forces.

The structure of the sensing element allows it to be subjected to over 10,000g shocks in any direction with a quick recovery, and then able to measure in the milli-g range with precision. The over-travel stops don’t engage until the sensor is subjected to ±400g’s.

All features are anisotropically etched from the same single-crystal wafer in order to take advantage of the mechanical characteristics of silicon, which has the density of aluminum and the strength of steel. The mechanical hysteresis of the silicon monocrystalline structure is immeasurably small.

The sensor die is a four leg, fully active, Wheatstone bridge. The bridge is formed by interconnecting ion-implanted resistors located on the four beams. Each beam contains two resistors, for a total of eight. Figure 6 shows a photograph of the middle layer containing the proofmass, frame, flexures, wirebond pads, and interconnecting metal traces that connect the piezoresistive elements. Gold traces are sputter deposited to connect the resistors and form wirebond pads. They also form bond rings that allow the attachment of the top and bottom caps.

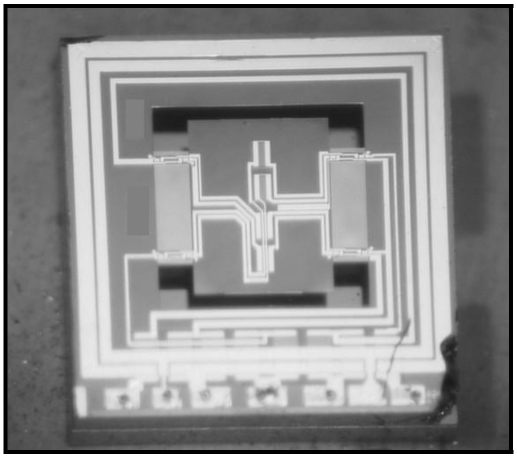

FIGURE 6 – SENSOR MIDDLE LAYER

When the transducer is subjected to acceleration in its sensitive axis, the proofmass deflects in relation to its frame. This causes four of the resistors to increase in value while the other four decrease. The output signal responds proportionally to the applied acceleration down to static levels. Figure 7 is an FEA model depicting the stress distribution in the flexures under load. The silicon wafer is boron doped to a level that provides a typical bridge impedance of 4,000 ohms.

The eight resistors are connected by metal traces and feedunders such that the effects of off-axis motion are canceled. This is realized despite the proofmass center of gravity being offset from the plane of the flexures.

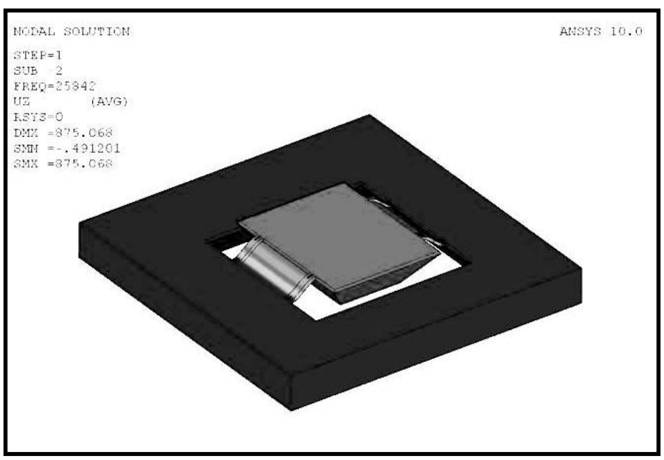

FIGURE 7 – FEA MODEL OF SENSOR ELEMENT

The sensors are singulated from bonded silicon wafers by a dicing saw with a potential yield of 570 pieces. Each of the wafers is etched using bulk micromachining which allows for much larger mechanical features as compared to surface micromachining. This translates into better measurement resolution and allows the electronics to be located off-chip without sacrificing accuracy.

The mounting of the sensor element is critical so as to avoid mechanical stresses being introduced through base strain. This can be due to bending moments from mounting or thermal coefficient of expansion differences between silicon and the packaging. Therefore, the sensor is mounted on top of a thick bond line of elastomer.

A vacuum bake is performed prior to sealing in a clean room environment. This removes moisture through a vent channel that is small enough to prevent particles from entering the sensor cavity. The seal is gold thermocompression.

SIGNAL CONDITIONING

The 4203 provides an analog single-ended output for each of the three axes with a full scale swing of ±2 volts and a bias of 2.5 VDC. The five wire cable also includes connections for power and ground. All of the conditioning circuit for the sensor element is contained within the transducer to provide a high level, low impedance output. Figure 8 is a block diagram with the following features.

1. A voltage regulator that applies a fixed 5 VDC excitation to the bridge. This allows the user's supply voltage to vary between 8 and 16 VDC without affecting performance.

2. A piezoresistive sensor element provides a differential Wheatstone bridge signal to the conditioning circuit, for common mode rejection.

3. There is a differential, unity-gain, second-order, low pass filter on each output signal leg of the bridge. With a Q of 0.5, the filter rolls off the unwanted high frequency content from extraneous vibration and keeps the gain stage that follows from saturating.

4. A digitally programmable IC normalizes offset and sensitivity, as well as corrects for temperature errors. It provides the gain in the circuit. It uses a piecewise linear temperature correction algorithm for sensitivity and zero adjust. There is no delay from circuit response since the digital correction is outside the analog signal path.

5. An output stage contains a unity gain sixth-order low pass filter. This combines with the first stage to provide an eighth-order roll off Butterworth characteristic.

6. Capacitors and inductors are located on each signal line, as well as on the supply line, to provide EMI/RFI protection.

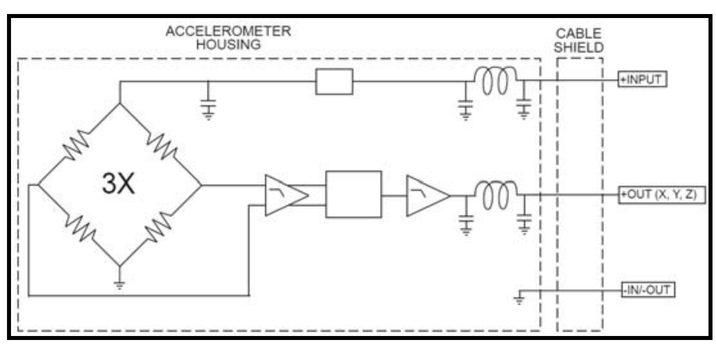

FIGURE 8 – CIRCUIT BLOCK DIAGRAM

The scale factors and zero measurand outputs of the sensor elements can differ between sensors due to manufacturing variation. Therefore, each accelerometer needs to be individually characterized at room ambient, and over temperature. The compensation network allows the accelerometers to be interchangeable with a total error band of only a few percent.

Various features have been incorporated to minimize susceptibility to conducted and radiated emissions. Each of the signal lines and the power lines includes in-line inductors and decoupling capacitors. The circuit boards have buried ground layers isolated from the case. The bulk of the sensor element has a field shield connection to bridge excitation for further protection. The cable has a braided shield for the user to connect to a common ground. Since the aluminum surface of the accelerometer housing is conductive, the braid floats on the transducer end in order to avoid ground loops.

CONSTRUCTION

Thermosonic gold wirebonds connect the sensor to a ceramic substrate. The sensor element is mounted on the substrate and protected with a ceramic lid. The accelerometer housing contains five separate circuit boards, three of which are modules containing the sensor elements. These are bonded to the floor and two walls of the housing cavity in order to provide an orthogonal alignment. There are separate boards for the EMI/RFI filters and signal conditioning. Figure 9 contains the envelope drawing of the 4203.

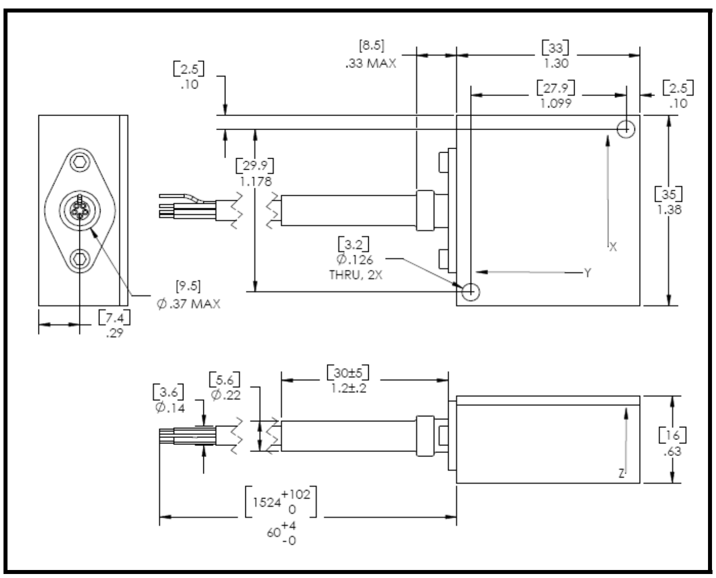

FIGURE 9 – ENVELOPE DIMENSIONS, inches [mm]

A custom flex circuit was developed to make the interconnections between the various boards as seen in Figure 10. The cable is securely anchored by an internal clamp arrangement on a separate adapter. There is an elastomeric strain relief at the cable exit. The adapter is then bolted to an aluminum housing. The cover is attached with screws as well. The completed assembly is encapsulated with a hard potting for environmental protection.

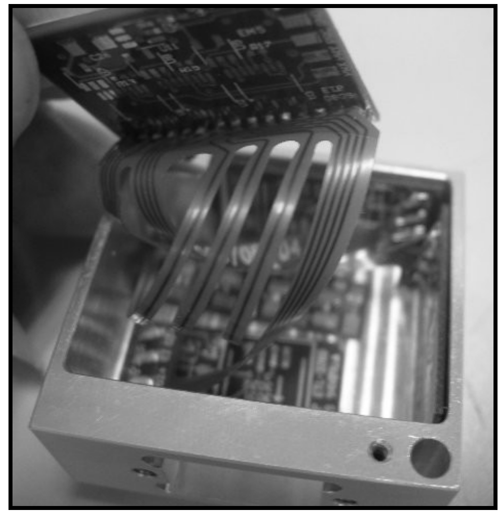

FIGURE 10 – FLEX CIRCUIT INSTALLED

MOTORSPORTS APPLICATION

The frequency response for standard Measurement Specialties accelerometers is normally determined by the damping and natural frequency characteristics of its sensor element. However, the Motorsports application requires a more limited passband for low frequency measurements in order to reject unwanted vibration signals at higher frequencies, both sinusoidal and random.

The sensor element and electronics in the 4203 must tolerate extraneous vibration levels beyond the passband without clipping. For example, an unwanted 500 Hz sinusoidal signal with a 300 g-peak was observed on an installation due to engine vibration. The signal was safely rolled off within the accelerometer without influencing low frequency content. This was accomplished by the judicious selection of over-travel stop locations in the sensor element and electrical filtering prior to the gain stage. Otherwise, this could result in the race engineer gathering corrupted data of which he may not be aware.

The 4203 is mounted near the center of gravity of the race car in order to measure whole body motion. Also monitored are longitudinal accelerations and braking forces. A triaxial accelerometer can measure heave (vertical), pitch (longitudinal), and roll (lateral). Frequencies below 40 Hz are typically examined for the general inertial measurement of the car.

During an actual race, real time data is transmitted to the racing team's design center. It has an identical car mounted to a seven post static rig. Hydraulic actuators are used to simulate the dynamic course conditions. This not only includes the track surface irregularities, but aerodynamic effects and track banking as well. The race engineer can then determine the optimum adjustments for the actual race car while the race is in progress, such as suspension stiffness and nose weight distribution. The accelerometer can also measure the vibration from a wheel that is unbalanced or has a flat spot.

The Z-axis of the accelerometer measures vertical motions, such as from bumps. On a systems level, this measurement can be combined with that of a skid sensor which measures impacts of the bottom of the car with the track surface. Thee skid sensor features piezoelectric film technology and is also supplied by Measurement Specialties.

TEST RESULTS

Table 1 contains the standard performance specifications for the 4203. Figure 11 has a frequency response plot of a 4203 provided for course testing. Note the -160 dB/decade roll off from the low pass filter set at a 100 Hz corner for this installation.

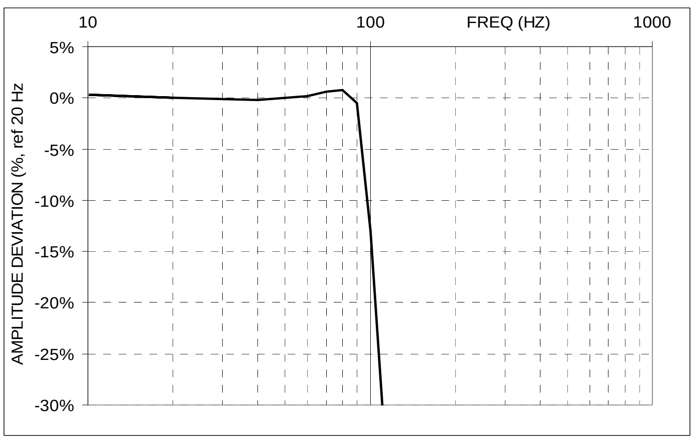

FIGURE 11 – FREQUENCY RESPONSE PLOT

Figure 12 contains a typical temperature response plot for sensitivity and zero offset. While the installation of the accelerometer within the driver compartment makes for a relatively benign temperature range, the accelerometer is capable of compensated performance over an operating temperature range of -54°C to +121°C.

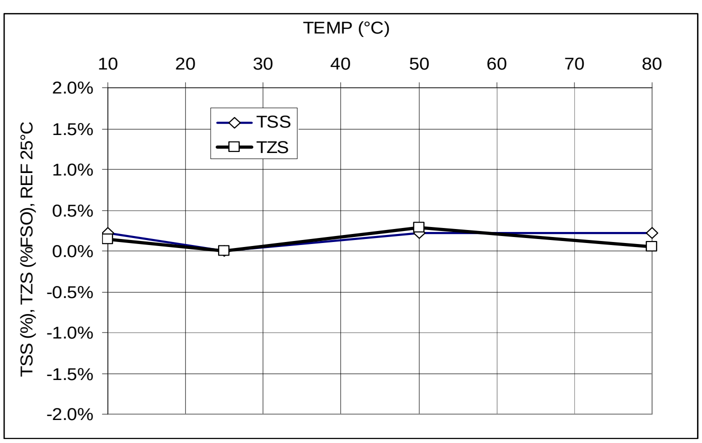

FIGURE 12 – TEMPERATURE RESPONSE

Figure 13 is a spectral density plot from a test run on an instrumented NASCAR race car that took place earlier this year in Milwaukee. It directly compares a 4203 that uses silicon MEMS to a conventional bonded metal strain gage accelerometer using fluid damping. The plot shows the results from the longitudinally mounted axis of the accelerometer. The outputs from the lateral and vertical axes have similar characteristics. The accelerometers were mounted just to the right hand side of the driver.

The low frequency peak is of most interest to the user. It illustrates the full body motion of the vehicle. The small peak at 30 Hz is at the frequency of the tire rotation and is caused by contact patch load variations. The advantage of the MEMS technology is evident. It removed all of the unwanted signals in the 140 Hz to 160 Hz range, which are mainly a result of engine vibration.

The challenge of the Milwaukee course is that it is relatively low speed with very little banking. Therefore, the acceleration signals are generally quite low compared to high banked, high speed ovals. The small inertial signals from the low banked track create a poor signal-to-noise ratio because of interference from the high speed noise from the engine. The 4203 performed well under these difficult conditions by effectively mitigating the high frequency noise as is clearly evident in the data presented. The 4203 has also been successfully tested at Nashville on a NASCAR stock car and on an Indycar race car in Sonoma.

CONCLUSION

Field testing has demonstrated that Measurement Specialties is able to provide an accelerometer that meets the rigorous needs of the Motorsports industry.

Modular construction permits a quick turnaround on custom accelerometer designs. Currently, each of the axes can be separately selected in ranges from ±7.5g to ±30g full scale. This is expandable to between ±2g and ±500g for custom requirements by the selection of available sensor elements. The eighth order filter corner can also be factory adjustable depending on the frequency content that the user wants to exclude. The standard corner filter corner is 60 Hz but the test results presented used a customer preferred setting of 100 Hz.

The basic need is to supply a device that ultimately permits the car to go faster. The Model 4203 is a triaxial accelerometer that is field proven for its accurate low frequency vibration measurements in severe dynamic environments.

REFERENCES

1. de Bruin, Diederik and Dunbar, Michael of IC Sensors, "New Accelerometer Based on Innovative Packaging and Circuit Design", SAE Technical Paper Series 951018, March 1995.

2. "Understanding Accelerometer Technology", Product Information Note; IC Sensors Products Databook 2002.

SPECIFICATIONS:

All values are typical at +24°C (+75°F) and 10Vdc excitation unless otherwise stated.

PARAMETERS					UNITS
DASH NO. (X, Y, AND Z AXES)	-7R5	-010	-020	-030	
DYNAMIC RANGE	±7.5	±10	±20	±30	g
SENSITIVITY ±10%	267	200	100	67	mV/g

PARAMETERS	VALUE	UNITS
ZERO ACCELERATION OUTPUT	2.5 ± 0.1	mV
TRANSVERSE SENSITIVITY	<3	%
COMBINED NON-LINEARITY AND HYSTERESIS (BFSL)	±1	%FSO
THERMAL ZERO SHIFT, 20 to 80°C (68 to 176°F), REF 24°C (75°F)	±2.5	%FSO
THERMAL SENSITIVITY SHIFT, 20 to 80°C (68 to 176°F), REF 24°C (75°F)	±3	%
EXCITATION VOLTAGE	8 to 16	Vdc
CURRENT	<30	mamps
RESIDUAL NOISE (PASSBAND)	1	mg-RMS
BANDWITH (-3dB FREQUENCY) -160 dB/decade rolloff	60 ± 10	Hz
INSULATION RESISTANCE (@50Vdc)	>100	MΩ
OUTPUT IMPEDANCE	<100	Ω
OPERATING TEMPERATURE	-40 to +125 (-40 to +257)	°C (°F)
MOUNTING TORQUE	6 (0.6)	lb-in (N-m)
MECHANICAL SHOCK (any direction)	5,000	g

TABLE 1 – MODEL 4203 TRIAXIAL ACCLEROMETER SPECIFICATIONS

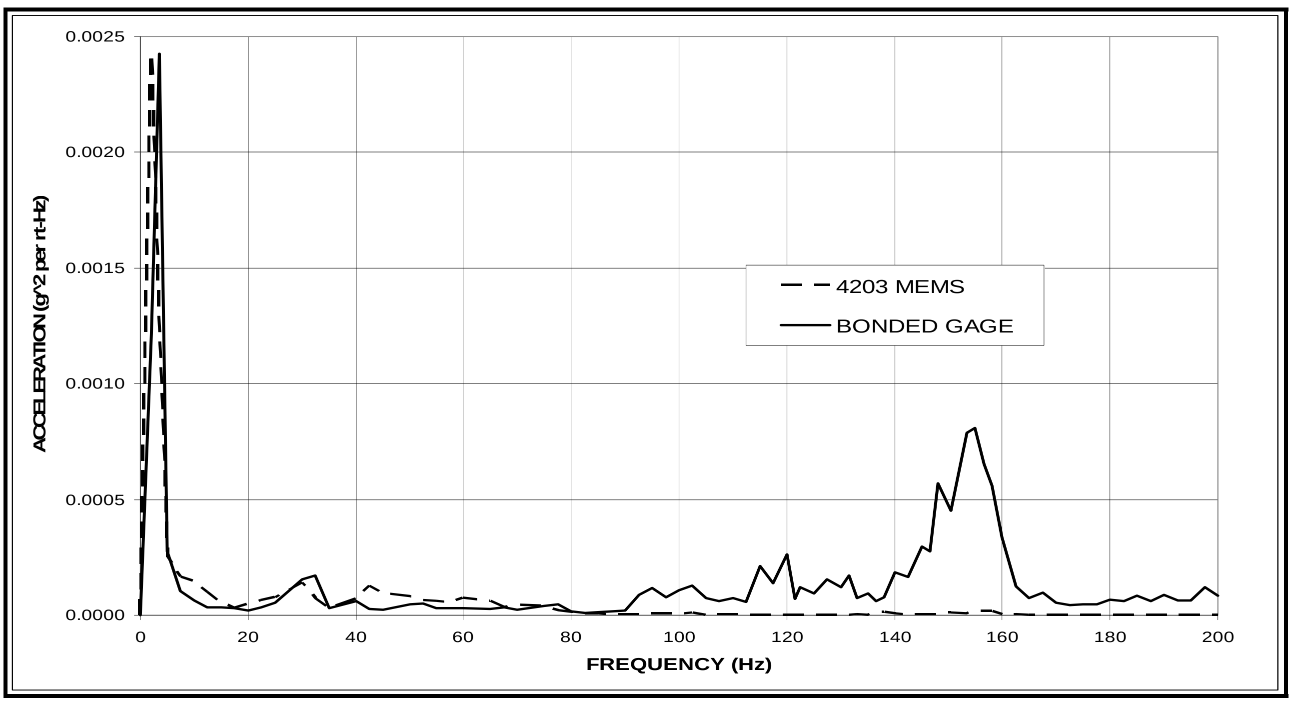

FIGURE 13 – SPECTRAL DENSITY PLOT FROM RACE TRACK TEST

CONTACT

Tom Connolly currently holds the position of Senior Design Engineer in the Vibration Division of Measurement Specialties, Inc. He was awarded a Bachelors of Electrical Engineering degree from Cleveland State University in 1978. He received a Masters of Business Administration from California State University Fullerton in 1993. He has been involved in transducer design since 1982. His transducer development experience includes the application of variable capacitance, piezoresistance, variable reluctance, inductive proximity, Hall effect, and magnetoresistive technologies. His present position specializes in the packaging and testing of MEMS technology sensor elements located at the vibration design center in Aliso Viejo, California (tom.connolly@meas-spec.com).