Improving a MEMS-based Sensor for Helicopter Gearbox and Rolling Stock Applications

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Abstract—**This paper describes work related to improving an accelerometer-based sensor used for monitoring a gear box in a helicopter and for monitoring rolling stock: the locomotives and cars used in trains. The sensor was designed to measure the speed of rotating shafts of up to 5500 RPMs and two versions were developed and successfully passed prototype testing: the first was installed on a pinion gear in a helicopter gear box and proven to work, and the second installed on wheel hubs of locomotives and freight cars of a 100-car train at the National Test Track Center in Pueblo, Colorado. A three-day test included a 10-hour, non-stop, 400-mile test run at a fairly constant 40 mph. The sensor was (and still is) the first to survive, intact and operational after that three-day test. Even so, a manufacturer wanted a more rugged sensor and better signal quality. Improving the ruggedness and signal quality of the sensor comprised two physical actions: relocation of components to address signal degradation and potting to prevent physical dislocation due to shock and vibration. The improvement achieved for the sensor for rolling stock accrue to the sensor used in helicopter gearboxes. The rationale, the methods, and the results of those improvements are presented in the paper. The paper provides an overview and introduction to using micro-electromechanical systems (MEMS), a practical application – a shaft-mounted, helicopter pinion gear, and a description of the test and results of that test. Ruggedizing details and test results are presented – to include comparisons of signals before and after the improving the ruggedness of the sensor and how improvements apply to the helicopter version of the sensor.**

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1. INTRODUCTION

Industrial equipment, robotics, and gear boxes that incorporate rotating shafts often need to monitor rotational vibration and shaft speed, as part of broader condition-based maintenance (CBM) systems. Fault detection equipment on drive systems, such as those use for land, sea, and air vehicles, typically use accelerometers mounted on transmission housing to capture, measure, and process vibration signals. The usefulness and flexibility of such detection equipment for applications involving rotating shafts, including pinion and planetary gears, have been limited by cabling, slip-ring approaches, and multiple sensors to obtain monitoring information. For more complex systems, especially those with poor signal transmission paths, a shaft-mounted, wireless solution based on a micro-electro-mechanical system (MEMS) is needed (see Figure 1) [1],[2].

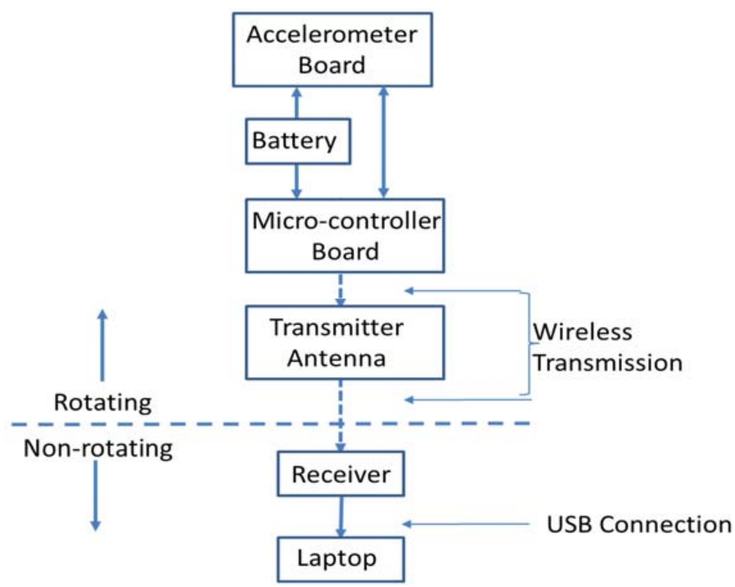

Figure 1. Simple MEMS block diagram [2]

An example applications include a prototype solution designed, developed, and embedded on a rotating shaft used in helicopter transmissions to capture and measure vibration signals, and from that, a MEMS version mounted on the wheel hubs of rolling stock [1],[2].

Helicopter Transmission: Pinion Gear—A specific application was the pinion gear of an OH-58C transmission (see Figure 2 and Figure 3). A NASA Glenn Research Center, Small Business Innovation Research (SBIR) award led to an experiment in which a tooth on the spiral bevel gear was pre-notched and then the transmission was run to tooth failure.

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The purpose was to prove the feasibility of shafted-mounted solutions and compare results with those obtained from traditional stationary, housing mounted accelerometer solutions.

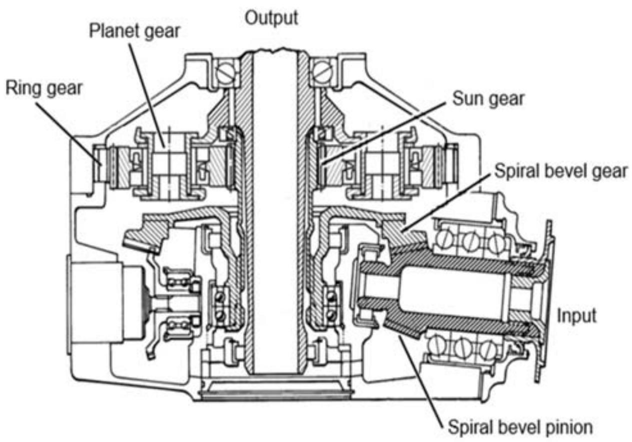

Figure 2. Illustration of an OH-58C transmission

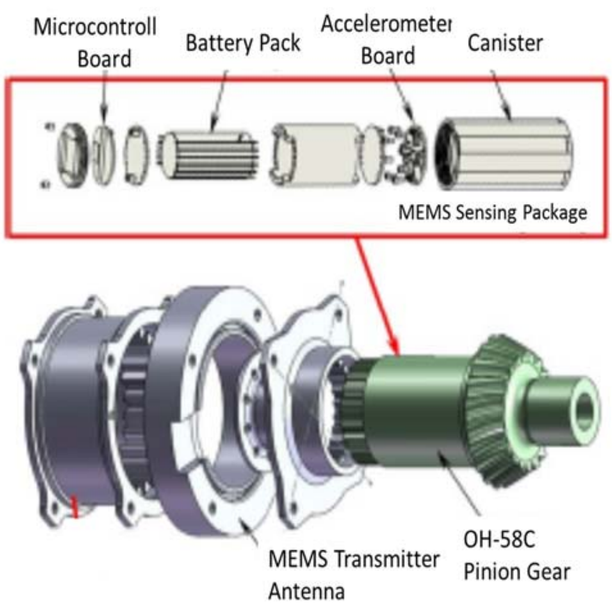

Figure 3. Diagram of MEMS sensor mounted on an OH-58C pinion gear

Figure 4 shows a partially disassembled MEMS sensor: the sensor comprises a microcontroller board, an accelerometer board, and a battery pack mounted in cylindrical canister.

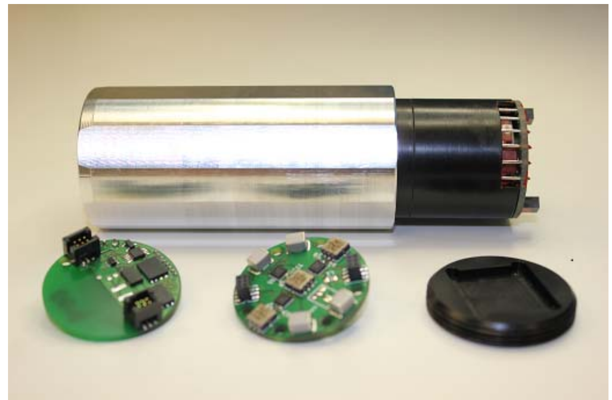

Figure 4. Canister, boards, and end cap

Wheel Hubs of Rolling Stock—A second example is the physical adaptation of the sensor for mounting on wheel hubs of the shafts of the trucks of train locomotives and cars (see Figure 5). This version of the MEMS sensor was designed and developed to prove feasibility for using such sensors to locate and identify anomalies related to railroad tracks.

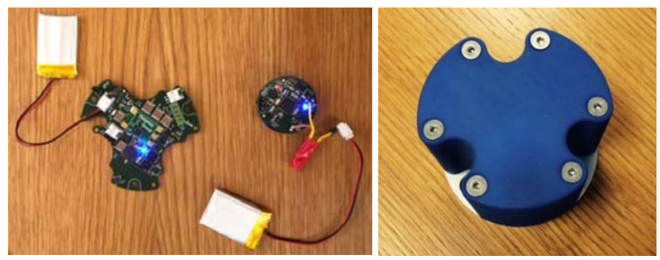

Figure 5. Boards with batteries and housing assembly

Referring to Figure 6, the adapted system comprises a MEMs sensor and a gateway to collect data, and write data to disk storage as files. The MEMS sensors were mounted on wheels of a train to produce shock data during test runs of a train over a High Tonnage Loop (HTL) test track (TT) to process the data, identify high-force events (HFEs), and locate the position on the HTL TT where HFEs occurred. The purpose was to demonstrate/validate an ability to support focused inspection of tracks to identify and locate anomalies requiring monitoring and service [2].

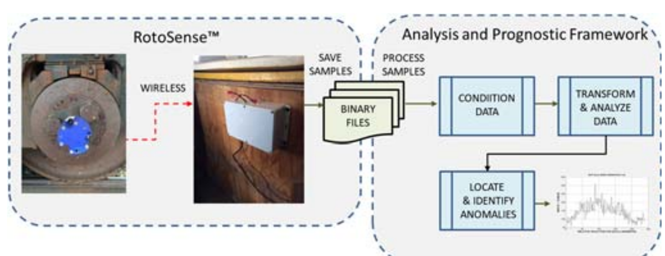

Figure 6. Block diagram of a rolling-stock sensor system

This paper presents initial results of applying the sensors to a helicopter transmission and to the wheel hub of a train car. Section three, Ruggedization, describes concerns and issues related to evaluation testing performed by an independent manufacturer of rolling stock. Those concerns and issues were fully addressed by solution approaches: physical potting of components, repositioning components, and updated software, firmware, and documentation, including new and improved functionality and descriptions. A description of the tests performed at NTS is described in section four, NTS Test Description, and section five, Improved Signal Qualify, presents the improvement in signal quality. The paper is ended with a summary.

2. Initial Sensor Testing Results

This section presents the initial results of testing a MEMS-based, shaft mounted sensor for two applications are presented: (1) sensor mounted on the shaft of beveled pinion gear in a helicopter transmission, and (2) sensor mounted on the wheel hub of a truck axle of a freight car of a train.

Helicopter Transmission: Shaft of a Beveled Pinion Gear

Triaxle-shaft-mounted MEMS sensors, RotoSense™, were installed on pre-notched OH-58C spiral-bevel pinion gears and endurance tests at NASA's Glenn Research Center were performed and run to tooth fracture failure: the notch was extended at run time = 51.9 hours and widened at run time = 106 hours: see Figure 7.

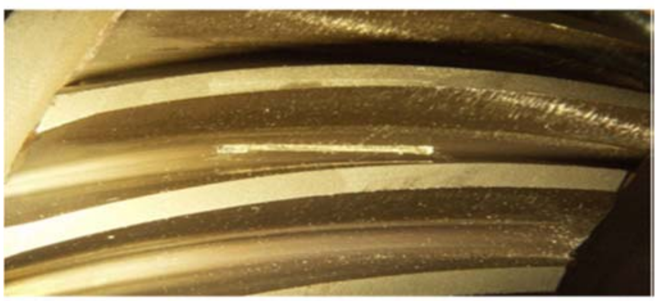

Figure 7. Final notching of the gear tooth

The sensors performed well, lasted the entire test, and all MEMS accelerometers gave an indication of failure at the end of the test. The MEMS systems performed as well, if not better, than the existing stationary accelerometers mounted on the gear box housing with regards to gear tooth fault detection (Figure 8).

Figure 8. Failed gear – fractured tooth.

For both the MEMS sensors and stationary sensors, the fault detection time was not much sooner than the actual tooth fracture time. The MEMS sensor spectrum data showed large first order shaft frequency sidebands due to the measurement rotating frame of reference. The method of constructing a pseudo tach signal from periodic characteristics of the vibration data was successful in deriving time-synchronous-average (TSA) signals (Figure 9) without an actual tach, and proved an effective way to improve fault detection for the MEMS [1].

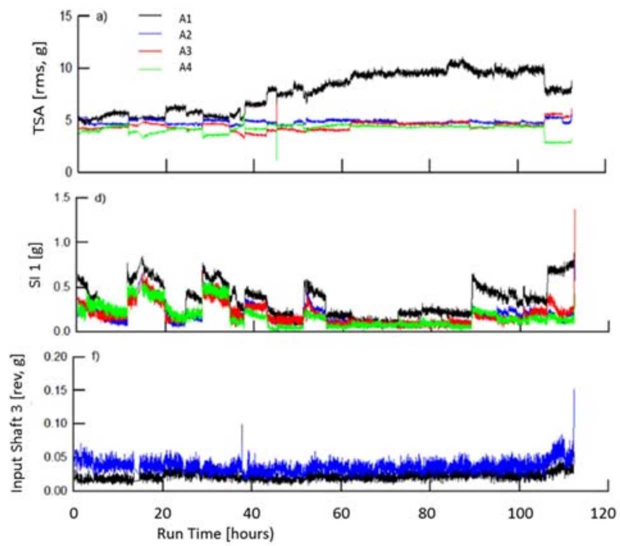

Figure 9. Example data: detection, condition indicators

Rolling Stock: Wheel Hubs of Truck Axles

Test Train—A test train at the National Test Track Center at Pueblo, Colorado, comprised three (3) locomotives and 110 freight cars and was run on a high-tonnage loop (HTL) test track (TT) used for research under heavy axle-loads to test track-component reliability, wear, and fatigue.

Test Track—The HTL track length is 2.7 miles divided into test sections that generally correspond to tangents, spirals, curves, and turnouts that are populated with features and test sections, as seen in Figure 11.

Table 1 lists the features of the TT, some of which are shown in Figure 12 and Figure 13. Fast-train operation is restricted to a maximum 40 miles per hour.

MEMS Configuration and Test Setup—The configuration for train applications includes a MEMS sensor, supporting firmware and software to support collecting, wireless transmitting of data to a gateway, and saving data in binary files. The assemblies are mounted to the wheel hubs to rotate with the axle so any anomalies in the wheels or track can be detected. The MEMS is configured as a three-axis accelerometer with 57mV/g sensitivity with a 161 Hz sampling rate: sensor was mounted concentrically on each end of a freight car axle and also on a locomotive axle of a train (see Figure 10).

Figure 10: MEMS sensor mounted on a wheel hub

Train Movement—The train was auto-controlled to run 15 laps per hour: 4 minutes per lap and 38,640 samples per lap. Four test runs were started on four days in 2015: May 11 – May 14.

Table 2 summarizes the May 14 test run from 2000 to 0632 the next morning: 10 hours, 32 minutes and over 4 million sets of six-byte data. The train started to move about 30 minutes after the sensors were turned on: the train was moved to the test track and two laps of test conditioning were run. After that, the train was kept at a constant speed of 15 laps per hour (4-minute laps).

Table 1. Features of the HTL TT – refer to Figure 11

1. Lubricator	2. Steel Bridge	3. Crib Ties
4. 405 turnout and frog	5. Thermite Welds	6. Rail Temperature
7. Rail Performance Test	8. Concrete Bridge	9. LTM Tests
10. Machine Vision	11. Fiber Optic cable	

Table 2. Summarization of the test run started on May 14, 2015

Description			Comments
Train	3 locomotives 110 cars		6,780' long (1.3 miles). Hopper car lengths, coupler to coupler, range from ~58.5 to 60.5 feet: used 60-foot length.
Build	92 minutes		2000 start; 2132 completed build
Run	540 minutes	132 laps	2132: started test conditioning run (TCR)
	17 minutes	2 laps	2149: completed TCR
	518 minutes	129 laps	2149 – 0627: testing
	5 minutes	1 lap	0632: end of test
Wheel 1	20645 files		
Wheel 4	20565 files		

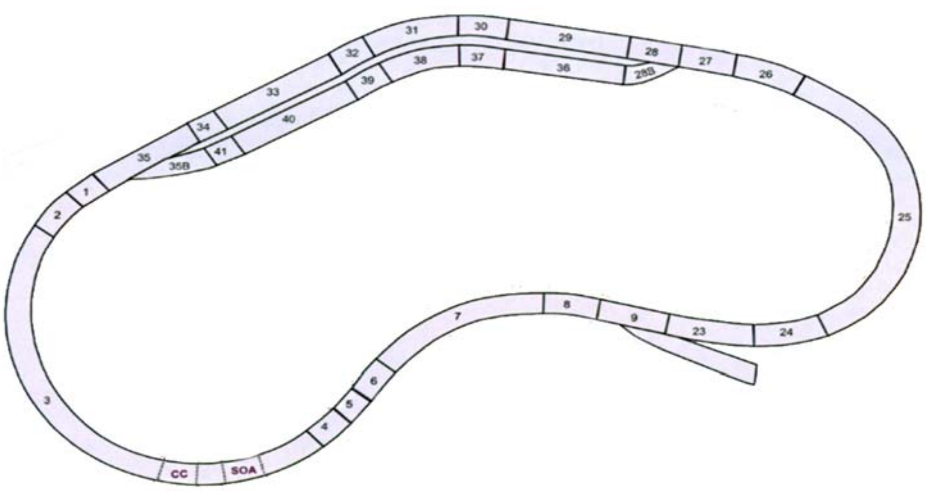

Figure 11. Layout of the Heavy Tonnage Loop Test Track.

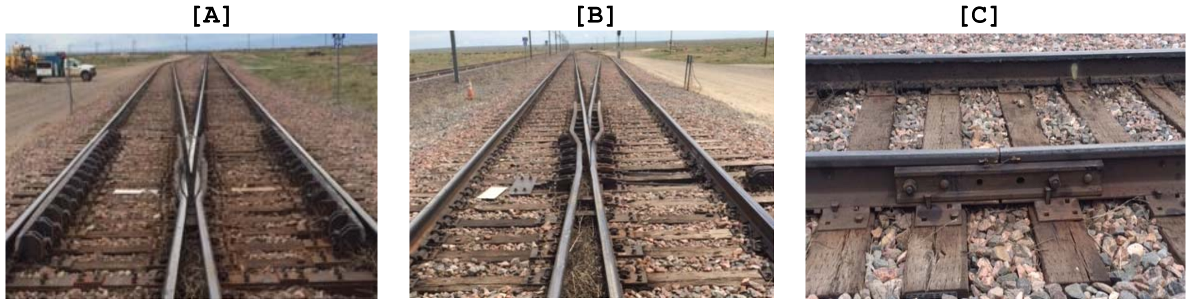

Figure 12. Turnout and frog, switch left [A] and switch Right [B]; steel bridge [C].

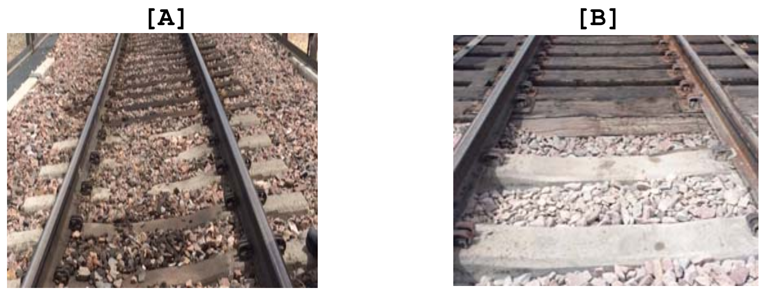

Figure 13: Concrete bridges [A]; crib ties, top of [B]; concrete bridges, bottom of [B].

Test Data—Data was collected and buffered for each axis at a sampling rate of 161 Hz and the buffered data was transmitted to a collection hub and saved in output files about once every 1.11 seconds. The data was analyzed, nominal values determined for zero-force conditions, and transformed into +/- values with respect to zero-force.

Data Analysis—Data analysis was hampered by the loss of Global Positioning Data (GPS) caused by a broken antenna. Consequently, raw data (see Figure 14) was analyzed by binning the data in terms of magnitude (xy-plane, the z-plane, and both planes) and relative laps (see Figure 15), examining the peaks, and comparing those peaks to features of the test track: pattern matching. We successfully proved that, even without GPS, we were able to synchronize the data to the start of the test track and then locate those features that could be located: as seen indicated in Figure 16 and Table 3.

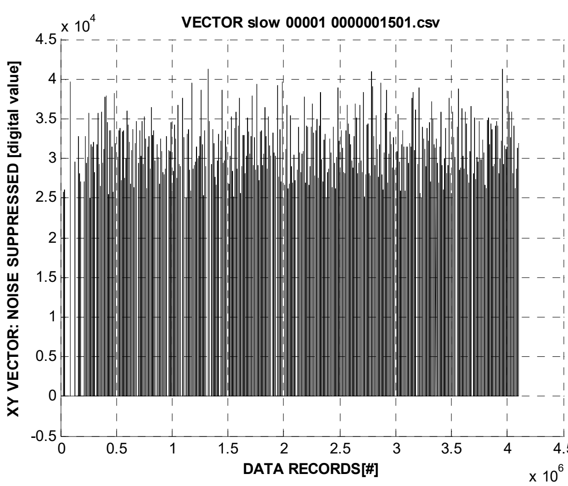

Figure 14. Raw data, xy-plane

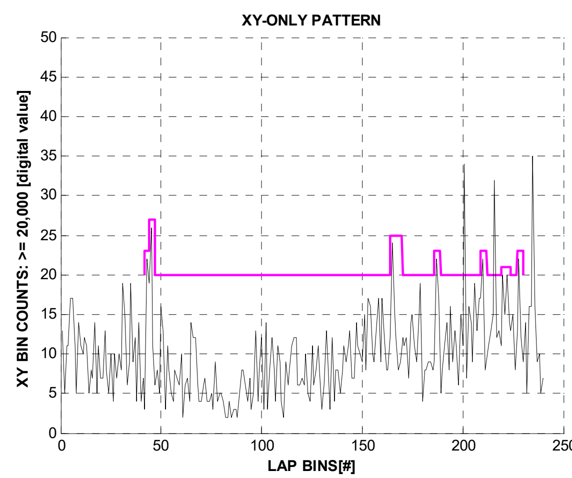

Figure 15. Binned data, xy-plane, by lap-bin number

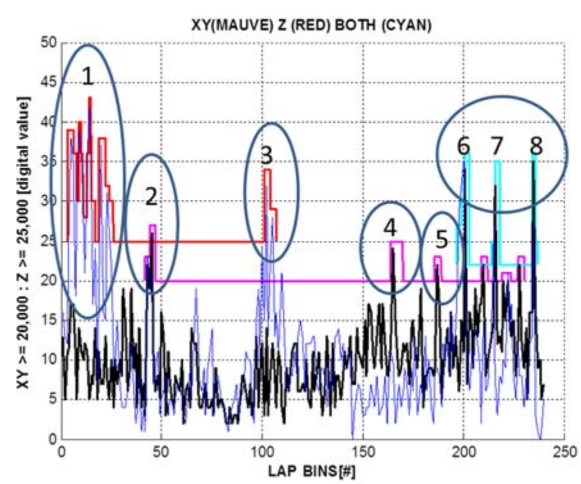

Figure 16. Data and identified features

Table 3. Test track description and detection evaluation

Track Sections	Feature Sections	TT ID	Track Feature	Detection Evaluation	
				XY-vector	Z-vector
1 – 3		S1	Lubricator	ND	ND
4 – 5		S2			
6 - 62	5-26	S3	Repair/overlay welds		Yes (1)
	30-40	S3	Concrete bridge	maybe	maybe
	42-46	S3	Concrete bridge	maybe	Yes (2)
63 – 66		S4	Steel bridges	ND	ND
67 – 69		S5	Bridge deflection	ND	ND
70 – 73		S6	Steel bridges	ND	ND
74 – 92		S7	Rail performance	ND	ND
93 – 97		S8	Fiber optic cable	ND	ND
98 – 108		S9	405 turnout/frog		Yes (3)
109 - 117		S23	405 turnout/frog		Yes (3)
118 – 125		S24	Lubricator	ND	ND
126 – 163		S25	TPO, Tie and fastener, performance	Yes (4)	
164 – 170		S26			
171 – 175		S27	Lubricator	ND	ND
176 – 180		S28	Turn out, steering switch, foundation	Yes (5)	
181 – 193		S29	LTM Tests	ND	ND
194 – 198		S30			
199 – 208		S31	FRA: Rail-seat deterioration, Thermite welds	Yes (6)	Yes (6)
209 – 212		S32			
213 – 225		S33	Crib ties	Yes (7)	Yes (7)
226 – 229		S34			
230 - 240		S35	407 turnout	Yes (8)	Yes (8)

Note: ND means Not Detectable.

3. RUGGEDIZATION

Subsequently, a manufacturer of rolling stock obtained sensor units and software and performed additional testing and evaluation. The units were found deficient because of the following: (1) physical failure at high-force testing of up to 100 g vibration and shock leading to board flexing and subsequent solder joint failures and battery displacement; (2) inaccurate vibrational readings caused by flexing of the printed circuit boards.

Operational concerns were reported in the following areas: (1) setting up communications between the Sentinel Gateway and Laptop; (2) setting up communications between RotoSense sensor and Sentinel Gateway; (3) sending commands to the RotoSense sensor; and (4) setting a synchronized time on a RotoSense sensor.

Solution Approaches

The following solution approaches were employed to address the issues and concerns: (1) employ potting; (2) reposition the PCB board and the battery; and (3) improve the quality of the built assembly to ensure an ability to withstand stresses and flexing due to high-g vibration and shock. Quality improvements also included inspections and procedures regarding use, assembly, and testing. In addition to hardware and software solutions, documentation improvements were made.

Final testing of the improved MEMS-based sensor, see Figure 17, was performed at the National Technical Systems (NTS) test facilities in Tempe, Arizona and at Ridgetop Group laboratories in Tucson, Arizona.

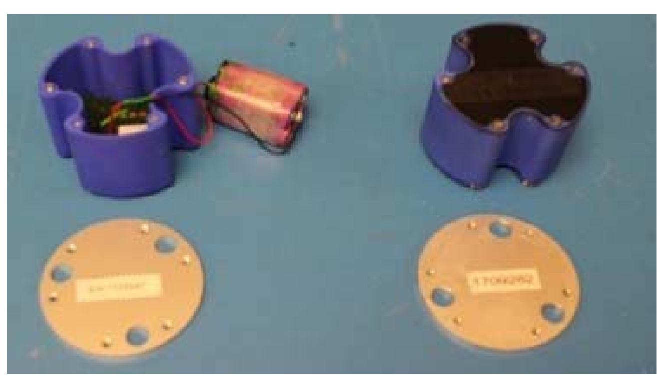

Figure 17. Original (left) and improved (right) sensors

Epoxy-based Potting—An epoxy-based potting was employed: (1) prevented battery displacement; (2) PCB protection from internal vibration and shock forces; (3) increased accuracy in sensor readings; and reduction of additional internal forces. Experiments were performed on sensor units with no potting, partial potting, and full potting. Partial and full potting addressed battery displacement, but partial potting did not fully address board flexing: full potting yielded the best results: zero defects related to shock and vibration occurred during initial and final testing conducted at Ridgetop Group and at NTS.

Component Repositioning—Experiments were performed using variations of component placement: the highest quality signals were obtained using the component placement shown in Figure 18.

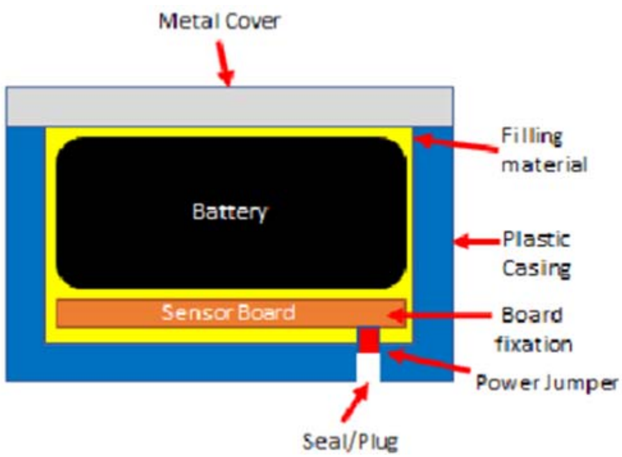

Figure 18. Component placement diagram

Software and Firmware Improvement—Supporting software updates include an updated file structure for more flexible control of future parameter changes. Firmware updates include the following:

1. Updated sensor-gateway communications
2. Updated gateway firmware to reduce timeouts
3. Sensor firmware, functional improvements:
    - Ability to change sensor node address
    - Ability to change the computer IP address for which the data is transmitted to
    - Set time on sensors
    - Read sensor temperature
    - Read radio frequency
    - Improved the wireless speed capabilities from 5.5KB/S to 11KB/S.

Documentation Improvement—The documentation was improved as follows:

1. Improved description of software commands
2. How to change sampling rates
3. How to change node addresses
4. Improved description of use and operation:
    - Procedure to turn off the firewall
    - Memory map functions
    - Operating as an administrator (Admin)

4. NTS Test Description and Results

Test plans were updated from one to three types of vibration test: (1) fixed frequencies, (2) sweep frequency, and (3) pulse (shock). Testing included those run at NTS in June of 2017.

Fixed Vibration Frequencies—Three vibration frequencies at seven levels of force defined and tested: Table 4. The sequences were run at four sampling rates: 160 s/s, 250 s/s, 500 s/s, and 1000 s/s.

No physical damage or anomalies were found. There was no loss of signal.

Table 4. Fixed vibration frequency

Vibration Frequency: Force
Dwell @ 50 Hz: 5g, 10g, 20, 30g, 50g, 70g, 100g
Dwell @ 100 Hz: 5g, 10g, 20, 30g, 50g, 70g, 100g
Dwell @ 250 Hz: 5g, 10g, 20, 30g, 50g, 70g, 100g

Sweep Vibration Frequency—The sweep frequency as defined as 10 Hz to 500 Hz at two different levels of force: 10g and 40g. The sequences were run at the defined four sampling rates.

No physical damage or anomalies were found. There was no loss of signal.

Pulse Vibration (Shock)—The pulse was defined as a six-millisecond, positive half-sine wave repeated five times at the six different magnitudes of force used for fixed-frequency testing. The sequence was repeated for each of four different sampling rates.

No physical damage or anomalies were found. There was no loss of signal.

5. IMPROVED SIGNAL QUALITY

After potting and repositioning of components, the signal quality is significantly improved as seen in Figure 19 through Figure 22.

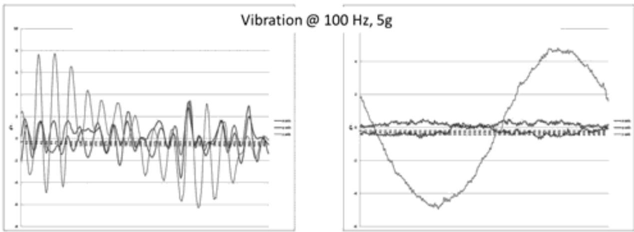

Figure 19. Vibration @ 100 Hz, 5g – before (left) and after (right) repositioning and potting

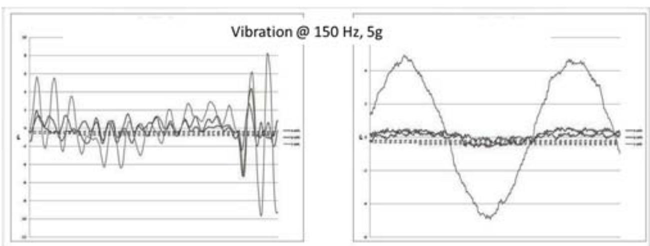

Figure 20. Vibration @ 150 Hz, 5g – before (left) and after (right) repositioning and potting

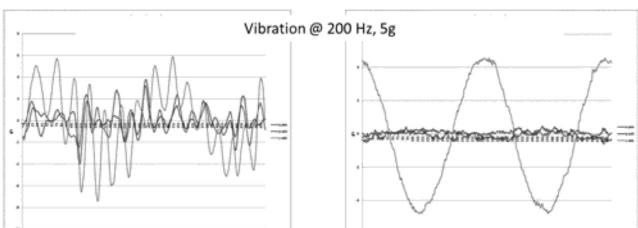

Figure 21. Vibration @ 200 Hz, 5g – before (left) and after (right) repositioning and potting

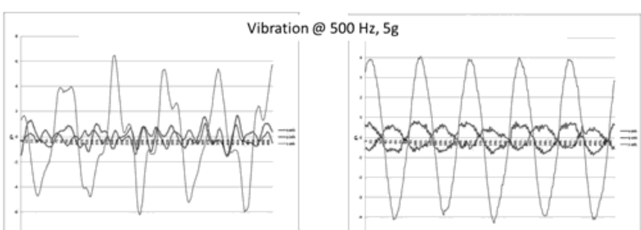

Figure 22. Vibration @ 500 Hz, 5g – before (left) and after (right) repositioning and potting

The output signals from the MEMS-based sensor after repositioning and potting of the boards and battery pack no longer exhibit extreme harmonic distortion and the amplitudes more accurately reflect the magnitude of the vibration force.

The bandwidth has also been improved from 4-6 Kb/s to 20-22 Kb/s.

6. GATEWAY IMPROVEMENTS

A new version of the Gateway for helicopter use is significantly more rugged: (1) it uses super strong Vicor power supply, that went through extensive power cycle testing on the Apache helicopter; and (2) all internal components are compact, soldered to a carrier board, and/or immobilized.

Also, the new Gateway is compatible with IoT sensors that can communicate through a Wi-Fi connection: at speeds up to 300 MB/s.

7. SUMMARY

Two versions of MEMS-bases sensors were designed and developed: one version for use in gear boxes of helicopters and the other version for hub mounting on axles of rolling stock. Each version of the sensors, their application, and their testing and results were described and the results evaluated: both versions functioned and operated successfully.

Subsequently, it was discovered the version for rolling stock was not rugged enough to pass 100 g vibration testing, and that level of testing was a customer required. After analysis and research, that version of the sensor was ruggedized by repositioning and potting of the components: the boards and the battery pack. The ruggedized version of the sensor was tested at NTS at various regimes: fixed frequency, sweep frequency, and pulse mode vibration at various frequencies and levels of force - no physical failure or anomalies occurred.

The quality (level of harmonic distortion) and the accuracy of measured force were proved by comparing signals from non-ruggedized to those from ruggedized sensors. In addition to ruggedization, improvements were made to the hardware to increase sensor bandwidth and to improve the Gateway with respect to ruggedness, to IoT compatibility, and to communication speeds. The software, firmware, and documentation were updated to increase communication, to reduce timeouts, and to increase functionality and usability.

Plans are to apply the potting approach to increase the ruggedization of the helicopter version of the sensor. That version has already been improved by increasing the sensor bandwidth, making the Gateway more rugged, and improving Gateway communications.

ACKNOWLEDGEMENTS

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BIOGRAPHY

James Hofmeister *has a B.S. in Electrical Engineering from the University of Hawai'i, Honolulu, Hawai'i and an M.S. in Electrical and Computer Engineering from the University of Arizona, Tucson, Arizona. He is also a graduate of IBM's Systems Research Institute (1986): Science and Engineering of Computer-oriented Systems. After a 30-year career with IBM and five years of retirement, he joined Ridgetop Group, Inc. in 2003, where he is a distinguished engineer in research and development. He specializes in many areas of engineering, including microelectronics, radiation-hardening, mixed-signal circuits and sensors, and support for diagnostics and prognostic health monitoring/management systems. His accomplishments include seven issued U.S. patents and over 40 published papers and articles. He is an IEEE life member, member of the IEEE Reliability Society, and a member of the Board of Directors of the Machinery Failure Prevention Technology conference, where he is chair of the Sensors Focus Group.*

Wyatt Pena *received a B.S. in Engineering Management with a technical minor in Systems Engineering from the University of Arizona. Wyatt grew up in the small mining town of Mammoth, AZ where he developed a diligent work ethic on his family's ranch. During the summer and winter breaks of his undergrad, Wyatt worked at the Silverbell Copper Mine in Marana, AZ. The short but well learned mining experience helped Wyatt lead a successful Senior Design Project, in which he and his team developed an Antenna Mast System for the Caterpillar 793F Large Mining Truck. Wyatt has been at Ridgetop Group Inc. for over a year and has played a key role on the design, development, and testing of numerous projects. Wyatt has expressed a sincere interest in prognostics and health management and would like to pursue a related Masters Program in the near future.*

Min Hudgins *Received an M.S. in Chemical Engineering from Arizona State University and a B.S. in Chemical Engineering from South China University of Technology in China. In 1996, she joined Burr-Brown Corporation as a Process Engineer in semiconductor manufacturing, and held Product Engineer and Test Engineer positions in Texas Instruments(TI) from 2000 to 2007, after TI acquired Burr-Brown, with responsibilities in product optimization and test development for Mixed-Signal Integrated Circuits. She joined Ridgetop Group, Inc. in 2015, and is currently a Test Engineer in product development.*

Robert Wagoner *Received degrees in Computer Science from the California State Polytechnic University, Pomona, CA, and California Institute of Technology, Pasadena, CA. As Ridgetop's Senior Vice President of Product Development, he is responsible for product development and manufacturing. He has also been leading the R&D of Ridgetop's key technologies in diagnostics, prognostics, and health management including hardware sensors, software algorithms, graphical user interfaces, and internet and network servivces. In addition to product engineering, patent activities, business and engineering management, Mr. Wagoner has co-authored conference papers, and he is an IEEE member and a member of the IEEE Robotics and Automation Society.*

Matthew Nielsen *received a B.S. in Electrical and Computer Engineering from the University of Arizona, Tucson, AZ in 2017. He joined Ridgetop Group, Inc. as an Electrical Engineer and has worked in analog/mixed signal circuit design and testing on multiple projects where he contributed in generating design requirements and modifications. His activites include hardware implementation, and test plans, execution, and documentation of results.*