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14. ABSTRACT Improvement of the operating characteristics of rolling-element bearings was sought through development and implementation of MEMS (Micro Electro-Mechanical System) based strain sensors. The strain sensors developed in this program employ a piezoresistive transducer to convert changes in applied strains to output voltages with an on-chip temperature detector compensating for thermal effects in the strain measurement. Bonding of MEMS strain sensors to application substrates was accomplished with induction heating using a wafer-level deposition					
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Report Title

MEMS FOR ROLLING ELEMENT BEARINGS

ABSTRACT

Improvement of the operating characteristics of rolling-element bearings was sought through development and implementation of MEMS (Micro Electro-Mechanical System) based strain sensors. The strain sensors developed in this program employ a piezoresistive transducer to convert changes in applied strains to output voltages with an on-chip temperature detector compensating for thermal effects in the strain measurement. Bonding of MEMS strain sensors to application substrates was accomplished with induction heating using a wafer-level deposition process to pre-coat Au/Sn eutectic alloy on the MEMS chips and a process to pre-coat steel substrates with a Ni/Au layer. A flexible-circuit board and a back-fill process were also developed for connecting MEMS strain sensors to signal-conditioning electronics. A wafer-level gold bumping process was used to place gold bumps on the MEMS chip solder pads and a thermo-ultrasonic bonding flip-chip technique was developed to bond the MEMS strain sensors to the flexible-circuit board. Performance evaluation of MEMS strain sensors was accomplished with the development of several high-precision test systems. For quick installation of MEMS strain sensors on application structures, a low-cost bolt-on displacement sensor and associated electronics were developed. Their usefulness was demonstrated on a public bridge structure using Timken's StatusCheck® 2.4 wireless data collection system.

List of papers submitted or published that acknowledge ARO support during this reporting period. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

Number of Papers published in peer-reviewed journals:

(b) Papers published in non-peer-reviewed journals or in conference proceedings (N/A for none)

Number of Papers published in non peer-reviewed journals:

(c) Presentations

Number of Presentations:

Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Peer-Reviewed Conference Proceeding publications (other than abstracts):

Number of Peer-Reviewed Conference Proceeding publications (other than abstracts):

(d) Manuscripts

Number of Manuscripts:

Patents Submitted

Patents Awarded

Graduate Students

<u>NAME</u>	<u>PERCENT SUPPORTED</u>
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FTE Equivalent:

Total Number:

Names of Post Doctorates

<u>NAME</u>	<u>PERCENT SUPPORTED</u>
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FTE Equivalent:

Total Number:

Names of Faculty Supported

<u>NAME</u>	<u>PERCENT SUPPORTED</u>
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FTE Equivalent:

Total Number:

Names of Under Graduate students supported

<u>NAME</u>	<u>PERCENT SUPPORTED</u>
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FTE Equivalent:

Total Number:

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Names of personnel receiving PhDs

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Total Number:

Names of other research staff

<u>NAME</u>

<u>PERCENT SUPPORTED</u>

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Inventions (DD882)

FINAL REPORT

PERFORMANCE PERIOD: March, 2005 – April, 2010

CONTRACT NUMBER: W911NF-05-2-0014

MEMS FOR ROLLING-ELEMENT BEARINGS

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**Final Report - March 1, 2005 through April 30, 2010
MEMS for Rolling-Element Bearings Program (Proposal Number 48371-EG)**

Executive Summary:

Objectives

The main objectives of the MEMS (Micro-Electro Mechanical Systems) for Rolling-Element Bearings (MFREB) Program were to improve the operating characteristics of traditional rolling-element bearings and the applications to which they contribute in two major categories. The first category was low-cost load sensing, overload protection, and condition/safety monitoring that can be applied equally to many bearing and non-bearing applications. The second category was investigation into the use of micro-asperities to improve lubrication and heat transfer phenomena in order to decrease friction and improve bearing life.

Approach

The effort of MFREB program was focused to improve the operating characteristics of traditional rolling-element bearings and the applications to which they contribute through the development and application of MEMS/microstructures in two major categories. The first category was development of low-cost MEMS strain-sensor modules and the means to bond them rapidly to steel and other structures in large quantities (> 10 million sensors/year). This technology opens the door towards providing low-cost load sensing, overload protection, and condition/safety monitoring for many applications such as monitoring of loads on a public bridge, a load-sensing application that was successfully demonstrated under this program. Also, strain-sensing on rotating structures was successfully demonstrated with the development of a module for wireless data telemetry and power coupling to a MEMS capacitive strain-sensor module. The second category was investigation into the use of micro-asperities to improve heat transfer and lubrication phenomena at the rib/roller-end interface and sealing locations. By virtue of the physical design of rolling-element bearings, these areas generate significant amounts of heat during operation, which contributes to rolling inefficiencies (e.g., friction), lubricant degradation, and loss of operating life.

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Significance

Rolling-element bearings are vital components of power-transmission devices. They afford low-loss rotational motion about a principal axis as well as critical structural support and load-carrying capability. Demanding power transmission applications such as transmissions, engines, gearboxes, wheels and drivetrains rely on rolling-element bearings.

Rolling-element bearings offer an opportunity for sensor integration. Bearings are precision devices, come in many shapes and sizes, and are responsible for carrying loads across rotational interfaces. A wide array of performance-critical applications demands high-strength steel bearings. Monitoring bearing operating characteristics such as load, temperature, and vibration can provide benefits: 1) insight into the health of a system, 2) process/operation control, 3) overload protection, and 4) bearing setting and alignment control. These benefits will be useful to many defense, industrial, and commercial applications.

Energy costs continue to rise. Bearings with lower friction seals to reduce fuel consumption and operating costs are in demand. For example, railroad operations could save approximately 2 - 3% in fuel costs/year just by decreasing the seal friction in a Timken AP (Class F) bearing by 40%. A major railroad in the US can consume approximately one billion gallons of fuel per year. Therefore, the cost savings from reductions in seal friction will be significant.

Micro-asperities on seals can decrease friction by retaining appropriate amounts of lubricants in desired regions of the seals. Lower friction seals will also have reduced operating temperatures. These lower temperatures and friction/wear surfaces will increase the life of the seals, which in-turn can increase the life of the bearing and surrounding components. This enhanced performance can also result in lower maintenance costs. Many defense, automotive, railroad, industrial, and commercial applications may enjoy the benefits of this low-friction technology.

Accomplishments

Listed below are highlights of major accomplishments of the MFREB Program:

1. Development of a prototype MEMS Resonant Strain-Sensor Module and associated electronics by the University of California Berkley (UCB) – **Final report of this effort was issued on March 1, 2007 by UCB.**

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2. Development of a prototype MEMS Capacitive Strain-Sensor Module and associated electronics by Case Western Reserve University (CWRU) – Final report of this effort was issued on December 31, 2008 by CWRU.
3. Development of a prototype MEMS Piezoresistive Strain-Sensor Module and associated electronics by Case Western Reserve University (CWRU) – Final report of this effort was issued on December 31, 2008 by CWRU.
4. Development of a demonstration unit for MEMS Strain-Sensor Remote RF Powering and Data Telemetry – Final report of this effort was issued on December 31, 2008 by CWRU.
5. Investigation of fabrication methods of deterministic asperities onto metallic surfaces using MEMS and roll-forming techniques and the effect of metallic surfaces with deterministic asperities on seal performance by University of Kentucky (UK) – Final report of this effort was issued on June 25, 2008 by UK.
6. Experimental investigation on the effects of deterministic micro-features on radial lip seal performance by The Timken Company in collaboration with UK – Final report of this effort was issued on March 26, 2009 by The Timken Company (Timken).
7. Laboratory evaluation of the above developed MEMS strain-sensor prototypes. As a result of this evaluation, Timken focused on the design, development and fabrication of a MEMS Piezoresistive Strain-Sensor Module capable of addressing the MFREB program objectives.
8. Development and fabrication of several MEMS Piezoresistive Strain-Sensor Modules.
9. Development of a rapid bonding technique using induction heating of eutectic alloys that provides strong bonding of silicon to steel and very good strain coupling.
10. Development of a eutectic rapid bonding process using induction heating for bonding MEMS piezoresistive strain-sensor modules onto steel substrates.
11. Design and manufacturing of flexible-circuit boards for interconnecting MEMS piezoresistive strain-sensor modules to the cables of their signal conditioning electronics.
12. Development of a thermo-ultrasonic flip-chip bonding process for bonding MEMS piezoresistive strain-sensor modules onto their interconnecting flexible-circuit boards.
13. Development of a eutectic rapid bonding process using induction heating for bonding MEMS piezoresistive strain-sensor modules with their attached interconnecting flexible-circuit boards onto steel substrates.
14. Development of a back-fill process using high temperature epoxy for securing bonded MEMS piezoresistive strain-sensor modules onto their interconnecting flexible-circuit boards.
15. Development of a back-fill process using high temperature epoxy for securing and protecting bonded MEMS piezoresistive strain-sensor modules and their attached interconnecting flexible-circuit boards onto steel substrates.
16. Development and fabrication of a bolt-on MEMS Displacement Sensor capable of measuring strain/displacements in one direction.

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17. Development of an automated 4-point bending calibration/test system for testing strain sensors when static extensional strains are applied.
18. Development of a uniform strain beam calibration/test unit for testing strain sensors when static and dynamic extensional strains are applied over a large temperature range.
19. Development of an automated shear-strain calibration/test system for testing strain sensors when static shear strains are applied.
20. Development of an automated calibration/test system for testing displacement sensors when static and dynamic displacements (x, y, z) and rotations (rotX, rotY, rotZ) are applied.
21. Development of an automated test system for measuring the response of displacement sensors to vibrations applied in the x, y, and z-directions.
22. Development of an automated test system for measuring the creep of strain sensors over a large temperature range.
23. Development of an automated long-term performance test system for measuring the performance of displacement sensors when static and dynamic extensional strains are applied over a large temperature range for long periods.
24. Integration of MEMS displacement sensor with Timken's wireless StatusCheck® 2.4 system for creating a wireless displacement sensing system.
25. Implementation of bolt-on MEMS displacement sensor for monitoring traffic loads on a bridge using both wired and wireless hook-up configurations.

Conclusions:

Over the past five years, developmental efforts at The Timken Company led to the fabrication of a prototype MEMS strain-sensor module having high fabrication yield and repeatability, producing high-accuracy strain measurements, having on-chip temperature measurement capability with low fabrication cost, and allowing rapid bonding to steel substrates. A rapid bonding/packaging process was also developed for bonding MEMS strain-sensor modules to steel structures. For easy implementation of MEMS strain-sensor modules, a low-cost, very sensitive, and rugged bolt-on prototype displacement sensor and associated electronics were developed capable of measuring displacements in one direction across a gap or solid section in a structure for real-world applications. In addition, seven high-precision test systems were developed for the performance evaluation of developed MEMS strain and displacement sensors. The usefulness of the bolt-on displacement sensor was demonstrated in a standard wired and StatusCheck® 2.4 wireless data collection system implemented on a public bridge structure. The conducted static test demonstrated good correlation between the standard

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wired and StatusCheck[®] 2.4 wireless data collection systems in detecting the weight of vehicles and their passage in traffic.

Technology Transfer

During the MFREB program duration, several progress reports and program presentations were presented to members of ARO and ARL as follows:

1. August 31, 2005 – Annual progress report
2. September 9, 2005 – Program presentation
3. September 30, 2005– Interim progress report
4. August 14, 2006 – Interim progress report
5. August 31, 2006 – Annual progress report
6. September 22, 2006 – Program presentation
7. March 15, 2007 – Interim progress report
8. August 31, 2007 – Annual progress report
9. June 30, 2008 – Program presentation
10. August 31, 2008 – Annual progress report
11. December 31, 2008 – Interim progress report
12. March 26, 2009 – Program presentation
13. April 30, 2009 – Interim progress report
14. August 31, 2009 – Annual progress report
15. July 30, 2010 – Final program presentation
16. July 30, 2010 – Final program report

A prototype Micro-Strain/Displacement Sensor made from metal-foil strain gauge was displayed on a Toolcat[™] (Utility Work Machine) at the SAE Commercial Vehicle Engineering Congress and Exhibition from October 30 to November 1, 2007 in Rosemount, IL.

A prototype Micro-Strain/Displacement Sensor made from metal-foil strain gauge was displayed on a Toolcat[™] (Utility Work Machine) at the SAE World Congress and Exhibition from April 14 to April 17, 2008 in Detroit, MI.

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A prototype MEMS Micro-Strain/Displacement Sensor made from MEMS piezoresistive strain-sensor module was displayed on a force-sensing beam at the SAE World Congress and Exhibition from April 14 to April 17, 2008 in Detroit, MI.

In January 2008, the potential application of MEMS strain sensors and displacement sensors to bridge usage and health monitoring was discussed with representatives of the Army's Engineering Research and Development Center (ERDC-GSL-MS and ERDC-GSL-MS).

In December 2008, a test was conducted to monitor the loads from traffic on a public bridge using several bolt-on displacement sensors made from MEMS piezoresistive strain-sensor modules. The conducted test included both wired and wireless hook-up configurations (using Timken's wireless StatusCheck[®] 2.4 system). An accompanying report was issued on April 30, 2009 describing details of the conducted test.

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**Final Report - March 1, 2005 through April 30, 2010
MEMS for Rolling-Element Bearings Program (Proposal Number 48371-EG)**

Program: MEMS for Rolling-Element Bearings
Project: MEMS Piezoresistive Strain-Sensor Modules for Low-Cost, High-Production-Volume Applications
R&D by: The Timken Company

Objectives

The main objectives of this project were to enhance the manufacturability and performance of the MEMS piezoresistive strain-sensor modules and to integrate, at the wafer level, a means to bond them rapidly to steel for low-cost, high-production-volume applications.

Approach

The emphasis of this project has been to enhance the manufacturability and performance of the MEMS piezoresistive strain-sensor modules and to integrate, at the wafer level, a means to rapidly bond them to steel for low-cost, high-production-volume applications. This work has been complemented by on-going research activities related to conceptual developments of MEMS piezoresistive strain-sensor modules. The approach includes finite-element analyses, Design of Experiments, and testing to optimize the design, the fabrication processes, and the bonding processes.

The MEMS piezoresistive strain-sensor modules employ a piezoresistive transducer in a full Wheatstone-bridge configuration to convert changes in applied strains into changes in sensor resistance. These changes in resistance (and hence the applied strains) are converted to output voltages by the signal-conditioning electronics, which can be located remotely through a wire connection. The modules use an on-chip platinum resistance temperature detector (Pt-RTD) to measure the temperature of the sensor in order to compensate for thermal effects in the strain measurement and to provide the valuable temperature information to the end user. A thermo-ultrasonic flip-chip (pick and flip chip over) bonding technique was utilized to form the interconnection between the strain-sensor module and the flexible-circuit substrate. The main advantages of this approach, when compared to other technologies, are lower cost and enhanced reliability.

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The goals for the MEMS piezoresistive strain-sensor module include the following: a strain resolution of 0.1 $\mu\epsilon$ (or better), an operating strain range from -1000 to 1000 $\mu\epsilon$, an operating bandwidth from DC to 10 kHz, a gauge length no greater than 1 mm, and an operating temperature range from -55°C to 150°C (with 1 hour excursions to 180°C). Some of the major challenges associated with making such MEMS strain-sensor modules were as follows:

1. Obtaining high-yield, highly repeatable manufacturability
2. Obtaining high-accuracy strain measurements
3. Obtaining on-chip temperature measurements with low fabrication cost
4. Developing a means, integral to the sensor, to rapidly bond the strain sensors to steel substrates
5. Developing a wafer-thinning process that exhibits high yield in high-volume production
6. Developing wafer-level deposition process for the eutectic alloy used in rapid bonding
7. Developing wafer-level gold bump bumping (formation of gold bumps on chip pads) process for flip-chip bonding to the flexible-circuit board using thermo-ultrasonic techniques

Techniques to rapidly bond strain-sensor modules to application substrates in high-volume-production applications are a key to great performance and low cost. These bonds must be strong and stiff enough to transfer the strain effectively from the steel structure, through the sensor's silicon base, to the transduction region of the sensor. Additionally, these bonds must last for long periods (greater than 10 years) in relatively harsh environments. These environments include a large temperature range and exposure to substances such as oil, grease, gasoline, and water. Another development in conjunction with the MEMS strain-sensor module is to develop bonding methods based on the use of eutectic alloys and induction heating. These developments in bonding provide many advantages over other bonding methods such as adhesives. For instance, induction heating is ideal for in-line production processes due to its ability to produce repeatable, rapid (under 10 seconds), and accurate heating cycles. In investigating various eutectic alloys to serve as the bonding layer, processes were developed using Au/Sn eutectic alloy as the bonding layer. In addition to the bonding process, development of processes were made to pre-coat the Ni/Au bond agent layer on the steel substrate and to pre-coat Au/Sn eutectic alloys on the backside of the MEMS chip with accurate film thicknesses and patterns.

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Significance

Rolling-element bearings are vital components of power-transmission devices. Bearings are precision devices that come in many shapes and sizes, and are responsible for carrying loads across rotational interfaces. They provide low-loss rotational motion about a principal axis, critical structural support, and load-carrying capability. Demanding power transmission applications such as transmissions, engines, gearboxes, wheels, and drivetrains rely on rolling-element bearings. Bearing failures are among the most costly and troublesome forms of breakdowns on mission critical machines. A failed bearing causes extended downtime and high repair costs, particularly when secondary machine damage occurs. Monitoring bearing operating characteristics such as load, temperature, and vibration can provide benefits useful to many defense, industrial, and commercial applications including the following:

1. Insight into the health of a system
2. Process/operation control
3. Overload protection
4. Bearing setting and alignment control

Strain sensors are critical components for the measurement of loads in bearings and structures. Strain measurement provides a powerful indication of the structure's condition, not only for maintenance and safety purposes, but also for evaluation of structure health in applications. There is an increasing need for miniaturized, highly sensitive strain sensors for industrial and military applications such as in aircraft, bridges, dams, tunnels, monuments, buildings, elevators, presses, machine tools, cranes, aerial platforms, agricultural machines, and other machinery. When compared to strain sensors made with other technologies, MEMS strain sensors based on piezoresistive silicon gauges are very rugged, sensitive, and high-bandwidth devices.

Accomplishments

At the beginning of this project, different piezoresistive strain-sensor technologies were studied and evaluated based upon their effective performance, reliability, and cost. At the end of this evaluation, fabrication of piezoresistive strain gauge in single-crystal silicon was chosen as the technology that could yield a fast, cost-effective strain-sensing solution for many applications.

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Based on this technology, developmental efforts began for a MEMS strain-sensor module with the following design constraints:

- Piezoresistive strain-sensing element in a full Wheatstone-bridge configuration with temperature compensation
- On-chip temperature-sensing element to measure accurately the temperature of strain-sensing region
- Gold bump bumping on the bonding pads at wafer level to provide the strain-sensor module with the capability of flip-chip bonding to flexible-circuit substrates
- Backside eutectic alloy deposition at wafer level to provide the strain sensor module with the capability of bonding to steel substrates
- Packaged sensing elements at wafer level to protect sensor module at the die level
- Remotely located electronics for higher temperature operation
- Low-cost fabrication
- Rugged construction

A piezoresistive strain-sensor module with the above design constraints requires a combination of key fabrication processes such as the formation of piezoresistors on a thin silicon wafer, formation of on-chip temperature-sensing element, wafer thinning, backside metal coating and patterning and front-side bumping at the wafer level. Figure SS1 shows a chip-level photograph of a MEMS piezoresistive strain-sensor module with an integral temperature-sensing element. Its fabrication steps may be grouped in the following set of manufacturing processes:

1. Strain-sensing & temperature-sensing element formation process
2. Wafer thinning process
3. Wafer back-side Au/Sn alloy deposition & patterning process
4. Wafer front-side gold bumping process

1. Strain-sensing & temperature-sensing element formation process:

In this project, development of piezoresistive strain-sensor module design and fabrication was divided into two phases. The first phase was identified as the Design of Experiments phase focused on process development for the piezoresistive strain-sensing element, wafer thinning process, and backside coating of S-Bond 220M alloy for rapid bonding. The second phase was identified as the Enhanced Design of Experiments phase where focus was placed on temperature-sensing element fabrication process, patterning by the lift-off process and forming a channel on the substrate backside by deep reactive ion etching to

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isolate the strain-sensing element from temperature-sensing element, backside deposition of Au/Sn eutectic alloy for rapid bonding, gold bump bumping on the bonding pads, and improving the overall strain-sensor module performance.

Table SS-1 summarizes the specifications of all wafer batches fabricated during the Design of Experiments and the Enhanced Design of Experiments development phases.

Figure SS2 shows the major fabrication steps for a strain-sensor module capable of flip-chip bonding to flexible-circuit substrate and of eutectic bonding to steel substrate. Its fabrication required eleven photo-masks whose functions in the fabrication photolithography are as follows:

1. Wafer align: defines the alignment marks
2. P+: defines the P+ region for good ohmic contact
3. Resistor: defines the bridge resistors
4. Contact: defines the interconnection metal to the bridge resistor contact regions
5. Metal1: defines the interconnection metals
6. Pad: opens the bonding pad and defines passivation layer of Si₃N₄
7. Pt: defines the Pt-RTD
8. Trench: defines the pre-cut and isolation on Pt-RTD
9. Under-bump metallization (UBM): defines the bumps in the gold bump bumping process
10. Protection: defines the protected area during UBM metal sputtering process
11. Back solder: defines the no Au/Sn area on the backside of the device

During the two development phases, several strain-sensor modules were designed and fabricated in accordance with Design of Experiments methodologies where variations of the following design and process parameters were implemented, evaluated and optimized in experimental test runs:

- Doping concentration in ion implantation for resistor formation
- Resistor width and length dimensions
- Straight and serpentine resistor shapes
- Temperature-sensing element design and process parameters
- Thick-wire solder pad design parameters
- Thin-wire bonding pad design parameters
- Isolation trench design parameters for temperature-sensing element
- Eutectic alloy deposition process parameters

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- Gold bump bumping process parameters

The piezoresistive strain-sensing element design in a full Wheatstone-bridge configuration (Figure SS3) was developed primarily during the first phase according to Design of Experiments methodologies where variations in doping concentration level, resistor shape, resistor width, and resistor length were initiated followed by an evaluation of their effect on the final resistance value. However, as indicated in Table SS-1, the final doping concentration level of $10E21 \text{ cm}^{-3}$ was obtained following the fourth wafer-batch fabrication during the Enhanced Design of Experiments development phase. The resistor parameter optimization process led to a long serpentine resistor shape in order to achieve the bridge high resistance within the available small wafer area (Figure SS4).

A platinum (Pt) based resistance temperature sensor (RTD) was also selected as the on-chip temperature-sensing element. Platinum was chosen because it has a high Temperature Coefficient of Resistance (TCR) value, linearity, chemical stability, and its properties do not change even with prolonged use at high temperatures. In addition, cost effective Pt-RTD fabrication processes compatible with the piezoresistive sensing element fabrication were used. The Pt-RTD element was integrated on the outer surface of the strain-sensor module to measure and provide more accurate temperature information to compensate for the thermal effects on the strain-sensing element. This allows the sensor module to be utilized over a wide range of application temperatures. Thin-film platinum was deposited on the silicon nitride insulation layer by an evaporation and lift-off process to yield the temperature-sensing element. The orientation of the temperature-sensing element was substantially diagonal with respect to each of the Wheatstone-bridge strain-sensing elements to reduce the axial stress/strain coupling between the sensor module and the application structure. From fabrication processing standpoint the main disadvantage of using platinum as temperature sensing material is its poor adhesion to silicon nitride (Si_3N_4) passivation surface. For this reason, an adhesive layer of 500 Å thick titanium (Ti) was deposited between the platinum thin film and Si_3N_4 . Due to chip-size limitations of the strain-sensor module, the total area of temperature-sensing element was limited to a 1 mm x 1 mm area. This constraint required small line spacing, which made the lift-off process more difficult for platinum thin-film patterning. Larger feature sizes offer higher fabrication yields. Therefore, there was a trade-off between feature size and fabrication yields. The RTD design was developed according to Design of Experiments methodologies where variations in platinum line-width, line-spacing, and line-length were initiated in three deposition test runs followed by an evaluation of their effect on the final RTD resistance value. Figure SS5 shows an on-chip Pt-RTD with the line width of 10 μm and spacing of 7 μm covering an area of 0.5 x 0.5 mm^2 .

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2. Wafer thinning process:

Finite-element analyses show that strain coupling improves as thickness decreases. However, it is difficult to handle thin wafers (thickness less than 100 μm). Wafer thinning is one of the most important aspects for the strain-sensor module. Wafer thinning eliminates ~96% of the initial thickness to only 30 to 50 μm . There are four primary methods for wafer thinning: deep reactive ion etching, wet etching, mechanical grinding, and chemical-mechanical polishing. The wet-etching technique was selected for this effort as a cost-effective method and specifically, the KOH wet etch was chosen to etch off the handle layer of the Silicon on Insulation (SOI) wafer and thin the SOI to the SiO_2 stop. Bonding and back-etch process was developed to thin the SOI wafer to the desired thickness, and a temporary wafer bonding technology was also developed to prevent the thin wafer from breaking when post processed. With the current bonding capabilities at the foundry, it is very difficult to get good bonds on flat wafers, unless a perforated carrier wafer is used. The edges of the wafers end up in contact with each other and sealing before all air is purged. Wafers with perforations bond better as the air can escape through the channels of the pattern before the material gets soft enough to planarize and fill the channels.

Commercially available bonding options were also investigated. One option was to use the EVG's wafer bonding equipment with the Brewer Science wafer bond material. Another option was to use perforated carrier wafers. A test run with plain Si dummy wafers was done first to make sure that the perforated wafers would be compatible with the KOH etch and the wafer bond itself would be sufficient. The dummy wafers consisted of a 2 μm thick SiO_2 layer sandwiched between a bottom SOI handle layer and a top layer of 30 to 50 μm thick Si. The top thin Si layer was acting as the device layer and the perforated carrier wafers were bonded to it. During the test run, the bonded wafer stack went through the KOH wet etch process to etch off the SOI handle layer to the SiO_2 stop. As the KOH etch process approached the thin Si layer on the perforated wafer, the KOH etch solution attacked the Si layer through the pinholes in the 2 μm SiO_2 layer. At this point, it was observed that the bonded stack started showing signs of delaminating and breaking apart. The consensus was that with the perforations, the Coefficient of Temperature Effect (CTE) mismatch between the carrier wafer and the very thin device wafer was putting enough pressure on the wafers to pull them apart. In addition, the required length of time in the KOH etch bath to remove so much of SOI material, allowed the KOH to affect the wafer bond through the carrier wafer perforations.

At the end of this test run, the use of EVG's wafer bonding equipment with the Brewer Science wafer bond material was chosen as the bonding method to fabricate the strain sensor module. As a result of the selected bonding and back-etch option, the wafer bonding quality for the 50 μm thin device wafers bonded onto Pyrex glass temporary carrier wafers (Figure SS6) was improved as well as the Au/Sn coating adhesion to the backside of the wafer. Improvement of the wafer bonding and back-etch process to thin the backside of the SOI wafer was also made by reducing the depth of the deep reactive ion etch

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along the saw street and the depth of the Pt-RTD isolation channel from 30 μm to 10 μm . This reduces the out-gassing from the coating material during the bonding pre-bake process and improves the overall bonding strength.

3. Wafer back-side Au/Sn alloy deposition & patterning process:

High yield of the backside metal coating is crucial to achieving high bonding strength. Major challenges existed in backside wafer metal-coating processes. The purpose of the backside Au/Sn coating and patterning is to form the adhesive layer, such as eutectic Au/Sn alloy, to provide the mechanical bonding to the application substrates, such as stainless steel. In this development effort, focus was placed on several key backside process steps that can be implemented to increase yield and adhesion.

A clean surface is important for good adhesion in coating processes. Investigation was made on the effect the cleanliness of silicon wafer backside had on the Au/Sn alloy film coating. The contamination effect on bond quality was examined by the tape pull test, which is an established test method for evaluating the quality of film coating adhesion. Generally, the tape pull test is a good indication of an adhesion problem; however, sometimes the coating can survive the tape test and still delaminate during the dicing procedure due to the ultrasonic vibration of the dicing saw. A Design of Experiments was conducted to identify the nature of the chemical residue created on the backside of the wafer after the KOH etch. The results clearly showed that a strong correlation between the contamination of the substrate and pull strength values exists. Furthermore, a contamination source and solution were determined.

On the fabricated wafers in the Enhanced Design of Experiments phase, the Au/Sn eutectic alloy underneath the temperature-sensing element was removed to decouple the strain from the application substrate using the backside Au/Sn layer patterning technique. Figure SS7 shows the patterned backside Au/Sn coating by the lift-off process technique. The clean patterned Au/Sn profile underneath the temperature-sensing element and saw street was successfully achieved by the lift-off process.

The conducted failure analysis showed that most of the bonding layer failure was from the nickel thin-film bonding layer. To improve the bonding strength, in the Enhanced Design of Experiments fabricated wafers, the titanium adhesion-layer thickness was increased from 500 to 1000 Å thick and the nickel bond-agent layer was decreased from 2500 to 2000 Å thick. Also the Au/Sn layer thickness was decreased from 10 to 5 μm . Subsequent bonding experiments confirmed the bonding strength improvement.

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5. Wafer front-side Au bumping process:

Compared to traditional wire-bond packages, wafer bumping offers attractive options that are essential for shrinking devices packed with more functionality: smaller footprint, reduction in overall package weight, better electrical conductivity, better thermal dissipation, lower inductance, interconnections that are mechanically more rugged and lower packaging cost compared to die-level processing. Depending on the package requirements, there are several wafer-bumping options available in the market today. In this effort, focus was placed on the electroplating of gold metal layers for the bump process flow. Several factors influence the choice of the bump composition, including manufacturability, bumping process capability and reliability. One key factor is the melting point of bump, which defines the maximum process temperature of the integrated strain-sensor module. The developed strain-sensor module has the Au/Sn eutectic alloy on backside of the device for direct bonding to application steel substrate. The melting point of the Au/Sn alloy is 278 °C which limits the entire sensor-module stack temperature range in post processes. The strain-sensor module would see about 320°C temperature for rapid bonding to the application substrate by induction heating, therefore, the bump material chosen should not be reflowed while the sensor module is under the induction heating cycle.

For flip-chip bonding of MEMS strain chips to flexible-circuit substrates, the electroplating gold bump bumping fabrication process was developed to be compatible with the wafer bonding and thinning process. Electrolytic plating technology provides the following advantages over other plating technologies:

- High reliability
- Fine pitch capability
- Flexible thickness & composition combination
- Low cost compared to other bump bumping processes
- Capable of high volume through-put

The developed bumping process for the MEMS strain sensor module combines advanced electroplating techniques with reliable implementation procedures to produce the high gold-bump bumping quality. It also incorporates a temporary polyimide protection layer to prevent the bridge resistors and Pt-RTD element from been electrically shorted during the electroplating gold-bump process. The curing temperature for the polyimide protection layer must be below 400°C otherwise the Si₃N₄ passivation film will crack the Pt-RTD element causing a decrease in chip yield. To this end, a 325°C low-temperature curing process was developed for the polyimide protection layer. The height and hardness of gold bumps are key parameters for reliable bonding results.

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During wafer thinning, the thickness of wafer bond coating-film in the bonding and back-etch process is about 25 μm and it must cover the entire wafer topographic. Therefore, the gold bumps (Figures SS8 & SS9) were made with a height of 20 μm and were annealed to have a hardness range of 35-75 Koop (~ 40-70 Vickers).

Conclusions:

Over the past five years, efforts were made to develop a MEMS strain-sensor module having high fabrication yield and repeatability, producing high-accuracy strain measurements, having on-chip temperature measurement capability with low fabrication cost, and allowing rapid bonding to steel substrates. In order to meet the above performance and fabrication constraints, the following sensor design and fabrication processes were successfully developed:

- Sensor design that provides high coupling of strain from the steel application structure, through the sensor's silicon base, to the sensor transduction region
- Wafer-thinning process that exhibits high yield in high-volume production
- Wafer-level deposition process for the eutectic alloy used in rapid bonding
- Wafer-level gold bump bumping process for flip-chip bonded to flexible-circuit substrates using a thermo-ultrasonic technique

As a result of the above developmental efforts, the final prototype MEMS strain-sensor modules (Figure SS10) exhibit the following performance characteristics:

- High sensitivity
- Strain resolution of 0.1 $\mu\epsilon$ (or better)
- High bandwidth: DC to 10 kHz
- Great stability
- Low hysteresis
- Excellent thermal properties
- Low-cost
- Extremely rugged for harsh working environments
- Rapid prototyping

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Technology Transfer

During the MFREB program duration, several progress reports and program presentations were presented to members of ARO and ARL as follows:

1. August 31, 2005 – Annual progress report
2. September 9, 2005 – Program presentation
3. September 30, 2005– Interim progress report
4. August 14, 2006 – Interim progress report
5. August 31, 2006 – Annual progress report
6. September 22, 2006 – Program presentation
7. March 15, 2007 – Interim progress report
8. August 31, 2007 – Annual progress report
9. June 30, 2008 – Program presentation
10. August 31, 2008 – Annual progress report
11. December 31, 2008 – Interim progress report
12. March 26, 2009 – Program presentation
13. April 30, 2009 – Interim progress report
14. August 31, 2009 – Annual progress report
15. July 30, 2010 – Final program presentation
16. July 30, 2010 – Final program report

A prototype Micro-Strain/Displacement Sensor made from metal-foil strain gauge was displayed on a Toolcat™ (Utility Work Machine) at the SAE Commercial Vehicle Engineering Congress and Exhibition from October 30 to November 1, 2007 in Rosemount, IL.

A prototype Micro-Strain/Displacement Sensor made from metal-foil strain gauge was displayed on a Toolcat™ (Utility Work Machine) at the SAE World Congress and Exhibition from April 14 to April 17, 2008 in Detroit, MI.

A prototype MEMS Micro-Strain/Displacement Sensor made from MEMS piezoresistive strain-sensor module was displayed on a force-sensing beam at the SAE World Congress and Exhibition from April 14 to April 17, 2008 in Detroit, MI.

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In January 2008, the potential application of MEMS strain sensors and displacement sensors to bridge usage and health monitoring was discussed with representatives of the Army's Engineering Research and Development Center (ERDC-GSL-MS and ERDC-GSL-MS).

In December 2008, a test was conducted to monitor the loads from traffic on a public bridge using several bolt-on displacement sensors made from MEMS piezoresistive strain-sensor modules. The conducted test included both wired and wireless hook-up configurations (using Timken's wireless StatusCheck[®] 2.4 system). An accompanying report was issued on April 30, 2009 describing details of the conducted test.

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MEMS Piezoresistive Strain-Sensor Modules

**Developed under the
MEMS for Rolling-Element
Bearings Program**

July 30, 2010

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Table SS-1: Specifications of fabricated MEMS wafer batches

Piezoresistive Strain Sensing MEMS Chips						
Device Parameter	Development Phase #1 Version #1 Chip MEMS-GEN1	Development Phase #2 Version #2 Chip MEMS-GEN2_Batch #1	Development Phase # 2 Version #3 Chip MEMS-GEN2_Batch #2	Development Phase #2 Version #3 Chip MEMS-GEN2_Batch #2a	Development Phase #2 Version #4 Chip MEMS-GEN2_Batch #3	Development Phase #2 Version #5 Chip MEMS-GEN2_Batch #4
Wafer Quantity	15	6	6	9	12	35
Doping Level	10E19cm ⁻³	10E20cm ⁻³	10E20cm ⁻³	10E21cm ⁻³	10E21cm ⁻³	10E21cm ⁻³
Bridge Resistance	~2.5kΩ	~7kΩ	~4kΩ	~4kΩ	~4kΩ	~4kΩ
Pt RTD Resistance	None	2kΩ	1kΩ	1kΩ	1kΩ	1kΩ
Trench Depth	50 μm	50 μm	20 μm	20 μm	20 μm	10 μm
Back-Patterned Au/Sn Coating Thickness	5 μm	5 μm	7 μm	7 μm	7 μm	10 μm
Device Thickness	100 μm	30 μm, 50 μm	30 μm, 50 μm	30 μm, 50 μm	50 μm	100 μm
Au-Bumps	None	None	None	None	Yes	Yes
Bonding	Wire Bonding, Solder Bonding	Wire Bonding, Solder Bonding	Wire Bonding, Eutectic Bonding	Wire Bonding, Eutectic Bonding	Wire Bonding, Eutectic Bonding, Flip Chip	Wire Bonding, Eutectic Bonding, Flip Chip
Development Status	Completed	Completed	Completed	Completed	Completed	Completed

Figure SS1: Chip-level photo of MEMS piezoresistive strain sensor module

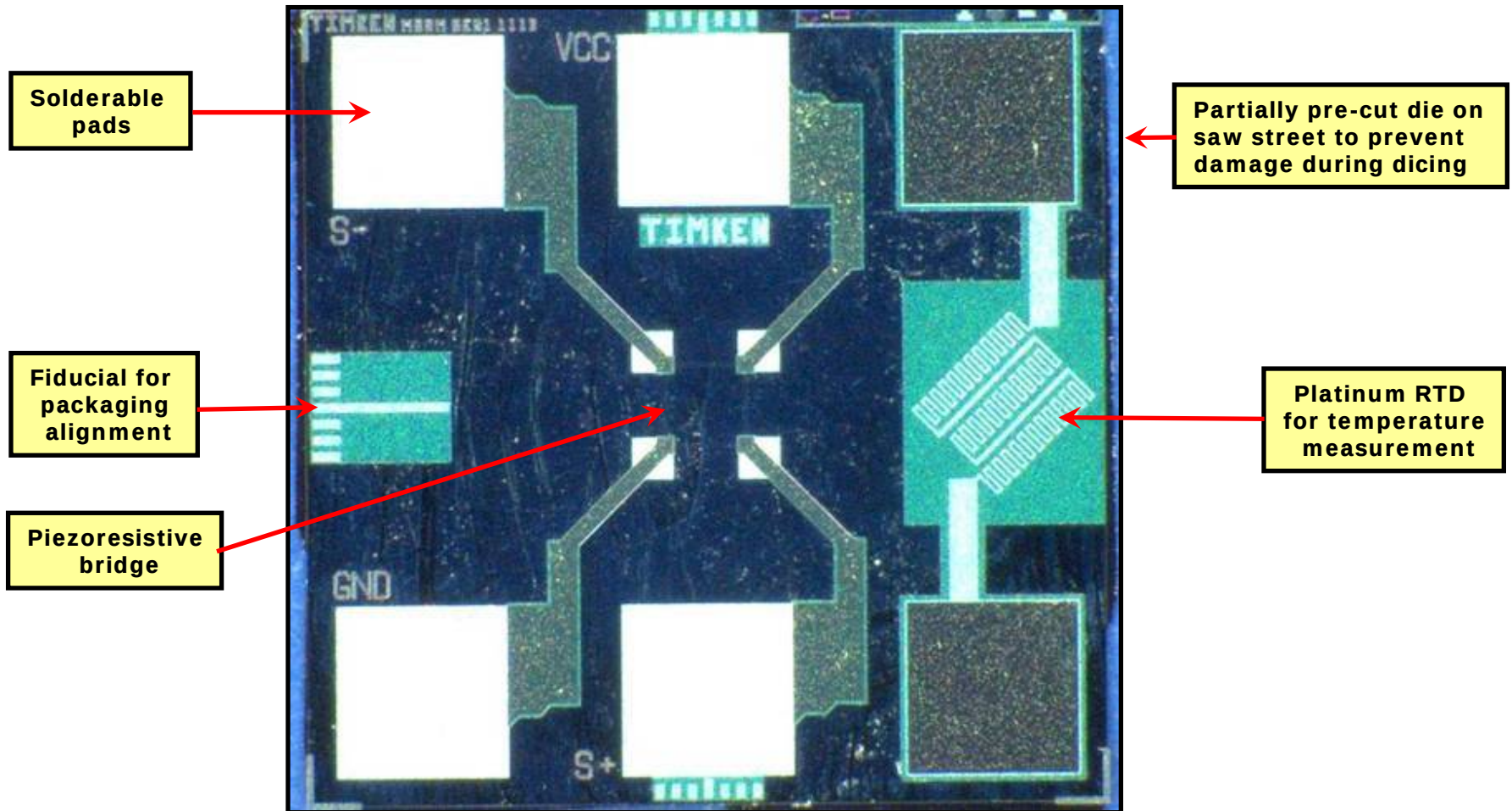


Figure SS2: Chip-level photo of MEMS piezoresistive strain sensor module

Major Fabrication Process Steps:

1. 100 μm thick N-Type SOI wafer
2. Thermal Oxidation
3. Implant B-Resistor, Mask Resistor
4. Sputter Al/Si/Cu, Mask Metal 1
5. Passivation: PECVD Nitride
6. Mask Pad, and etch pads
7. Sputter, or E-beam Ti/Pt, Mask Metal 2, Lift off
8. DRIE Trench process
9. UBM sputtering
10. Electroplating Au on the front side
11. Bonding on carrier wafer and SOI handle portion back etch by KOH wet etch
12. Mask Solder, deposition Au/Sn. And patterning by lift-off process
13. Remove carrier wafer to release the die

MEMS Piezoresistive Strain Sensor Fabrication Process Cross Section (not to scale)

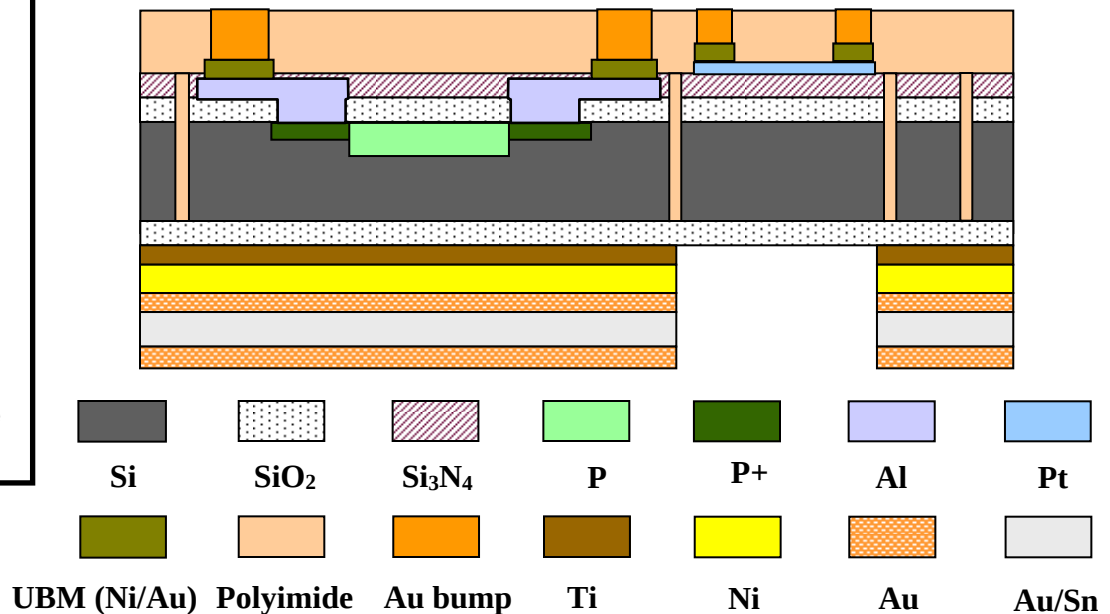
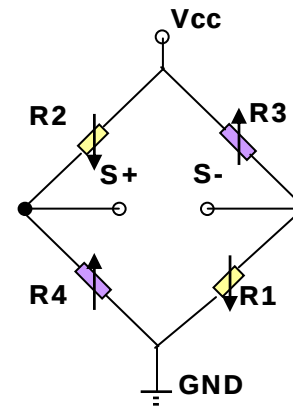
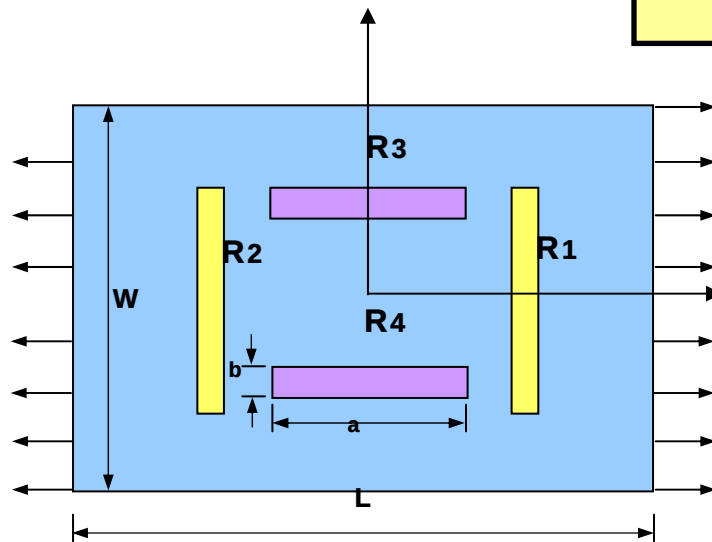


Figure SS3: Piezoresistive element in full Wheatstone-bridge configuration



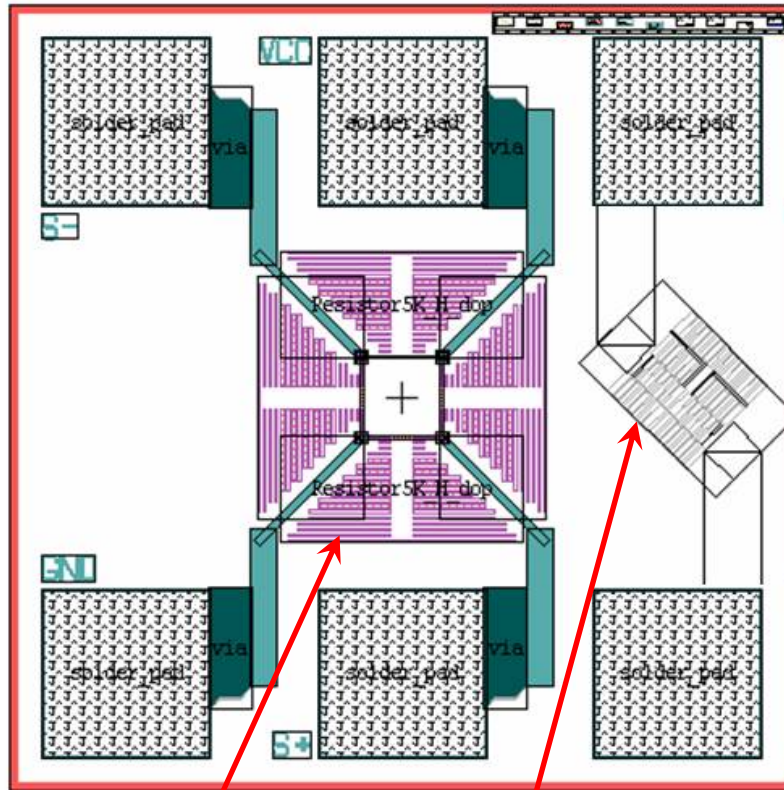
**Piezoresistive thermal effect and other common errors
minimized with full bridge configuration**



**Strain load along $\langle 110 \rangle$
Si-crystal plane**

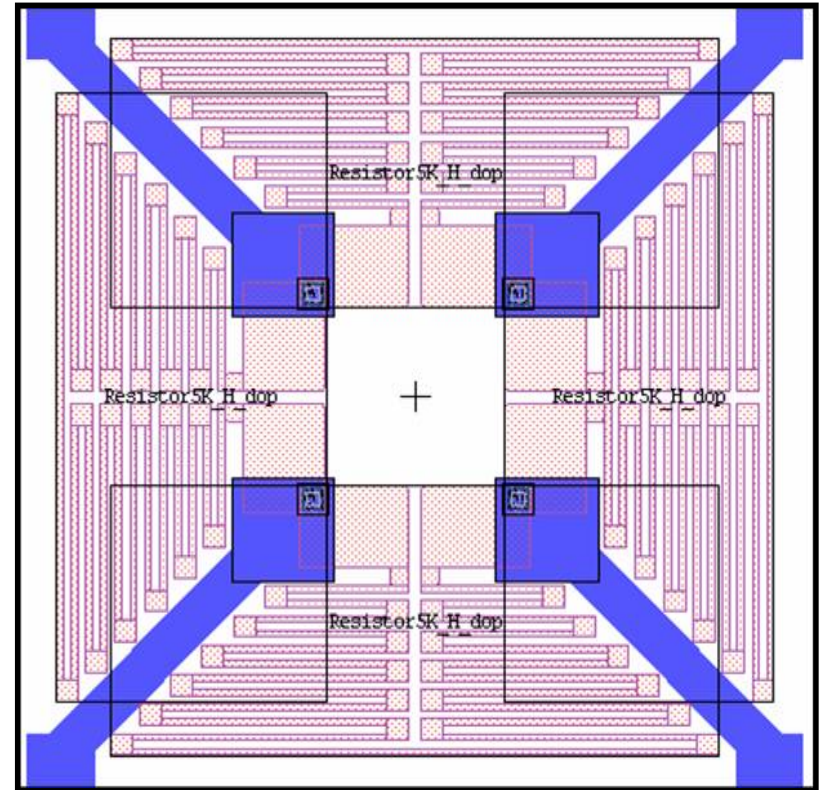
**P-Type Si resistors made on $\langle 100 \rangle$ wafer oriented in $\langle 110 \rangle$
strain/stress direction**

Figure SS4: Resistor design for ion implantation with high-doping concentration



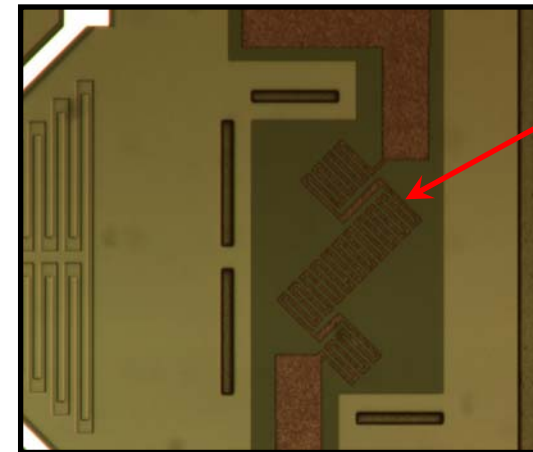
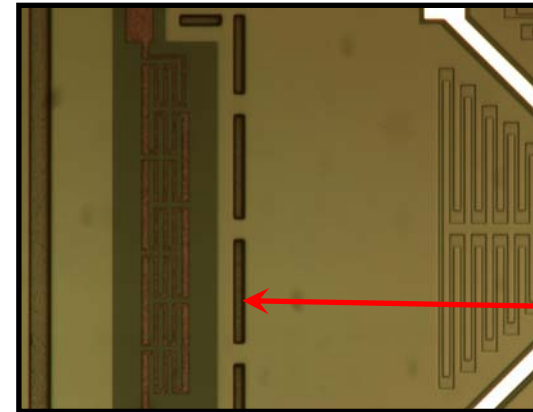
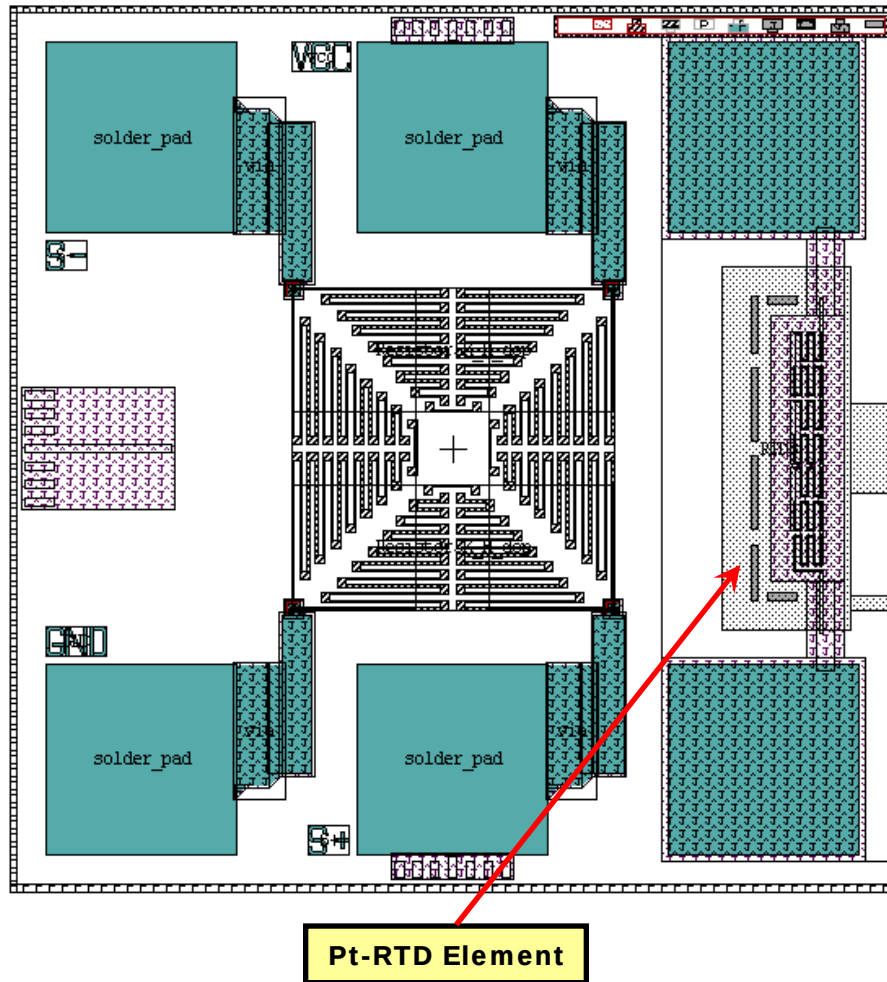
**Serpentine
piezoresistive
bridge**

**Pt-RTD element
for temperature
measurement**



**Close up view of serpentine resistor design
for ion implant with high-doping concentration**

Figure SS5: On-chip enhanced Pt-RTD element



Close up view of Pt-RTD design

Figure SS6: Device wafer bonded on Pyrex glass temporary carrier wafer

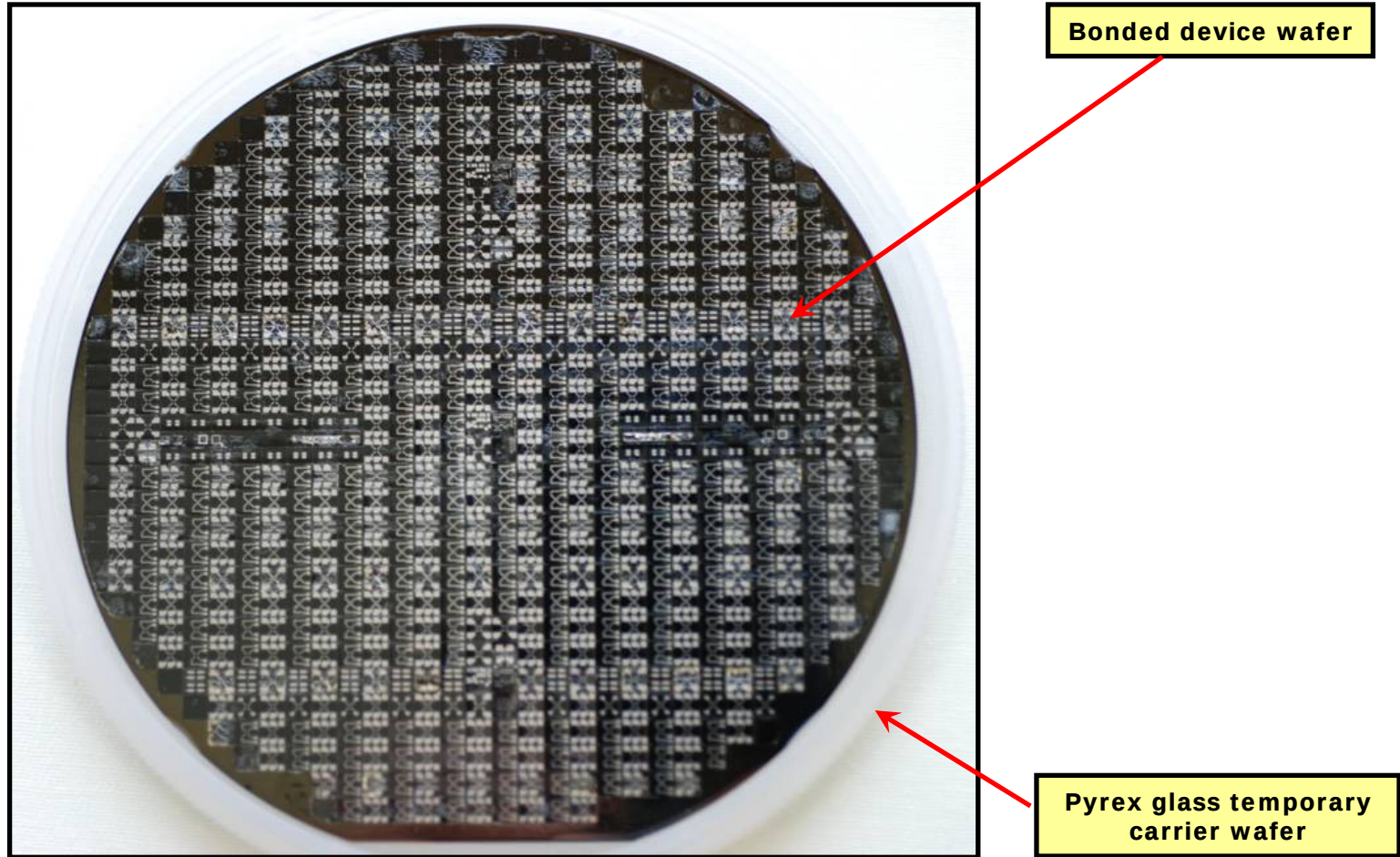
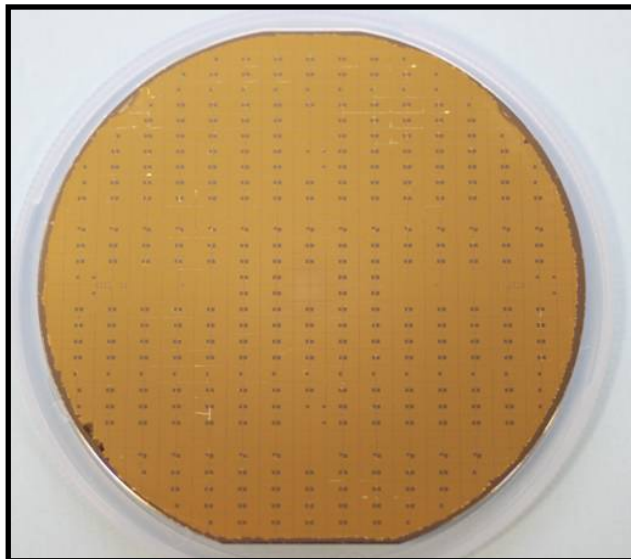
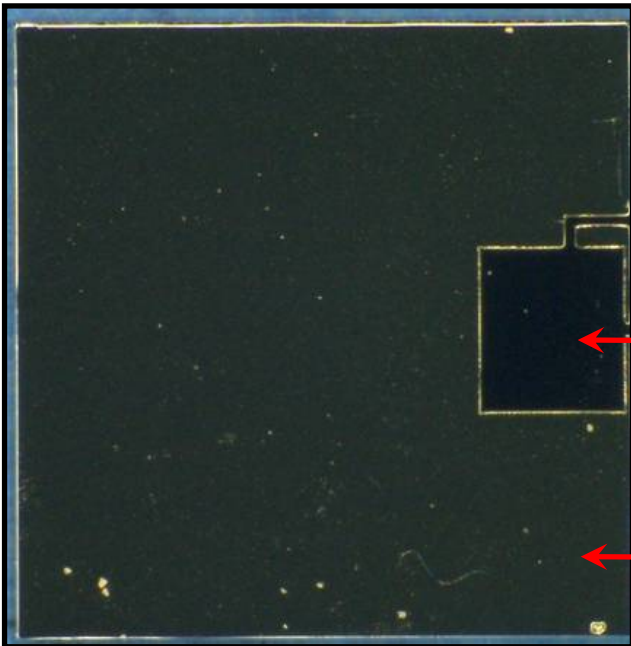


Figure SS7: Backside wafer-level Au / Sn patterning



Close up view of backside wafer-level
Au / Sn patterning



Removal of Au/Sn coating from underneath
the Pt-RTD area with the lift-off process to
isolate the strain coupling from the
application substrate to Pt-RTD

5 micron thick Au/Sn eutectic alloy
coated on the backside of the device

Figure SS8: UBM & gold bumps for MEMS strain sensor module

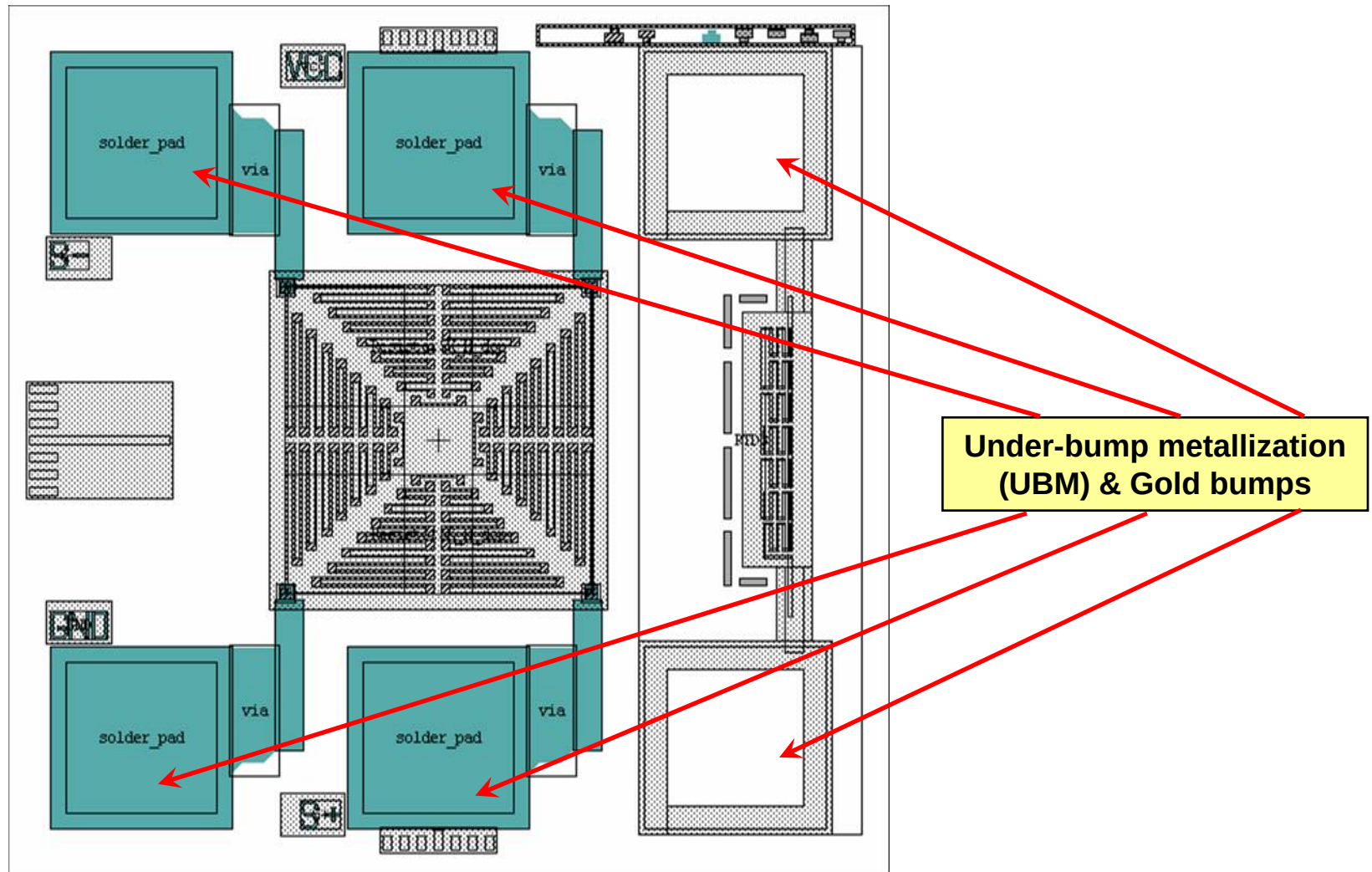
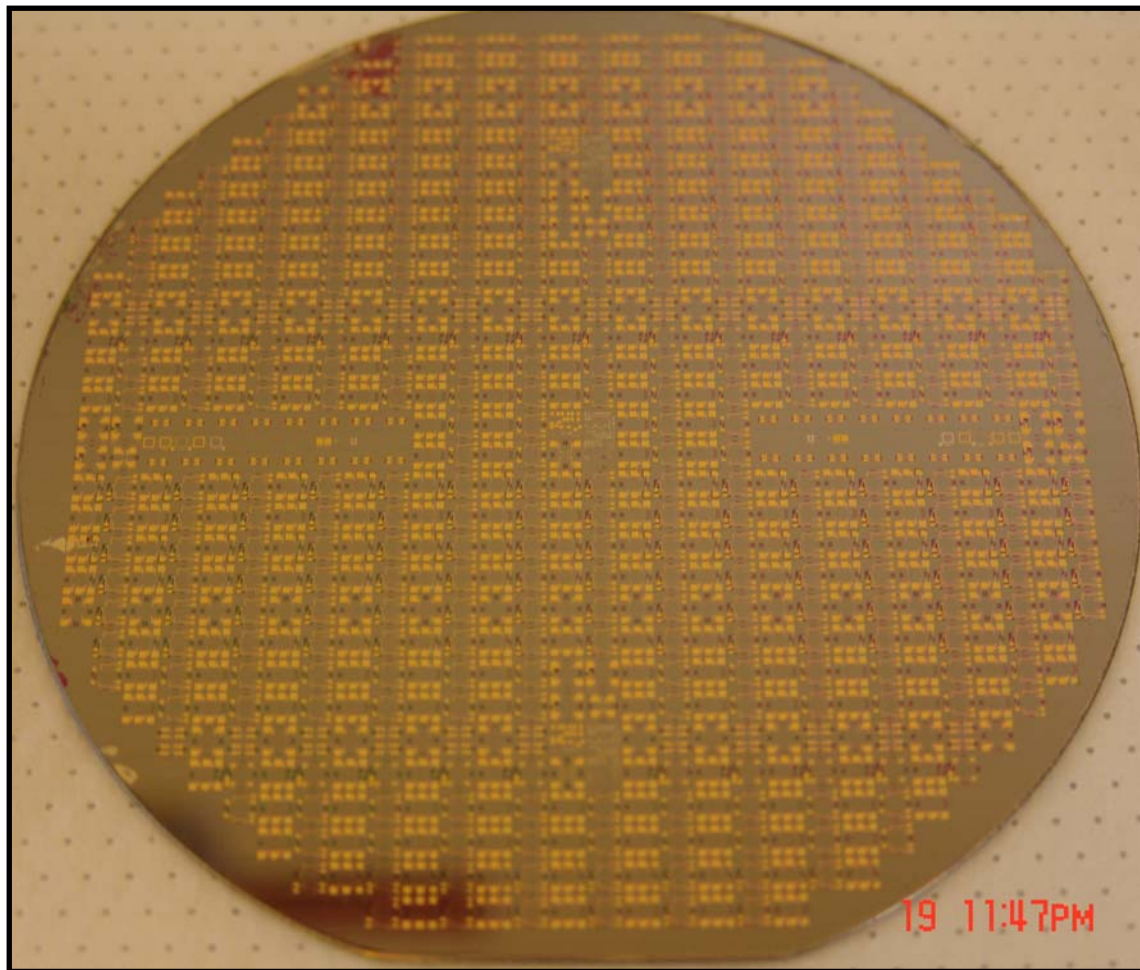
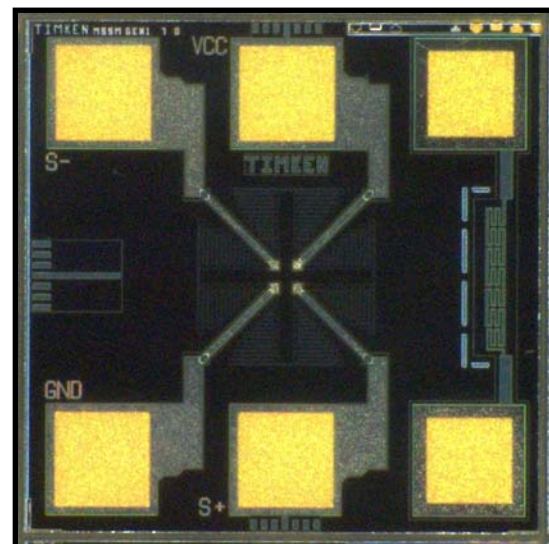
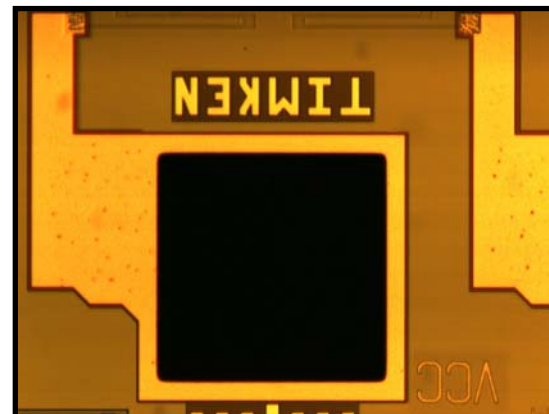


Figure SS9: Gold bump bumping process



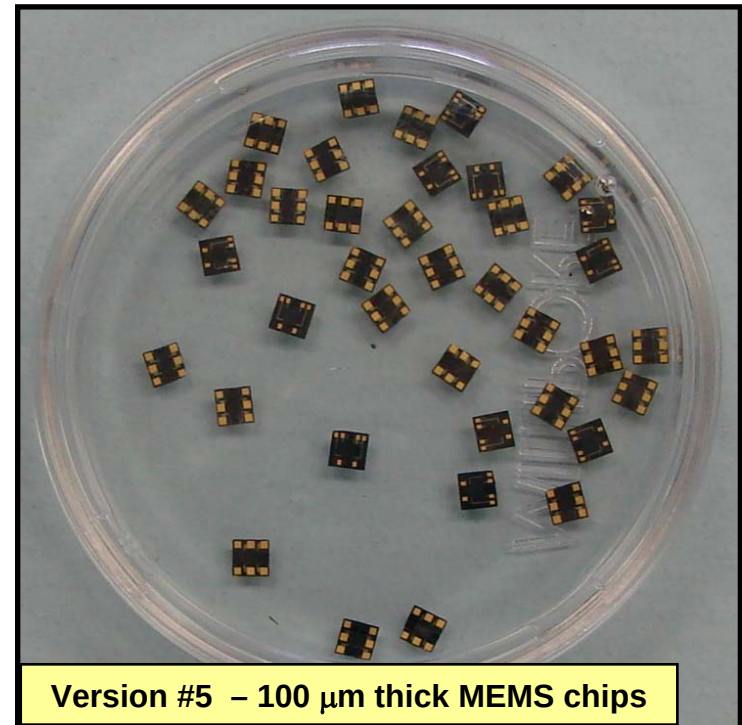
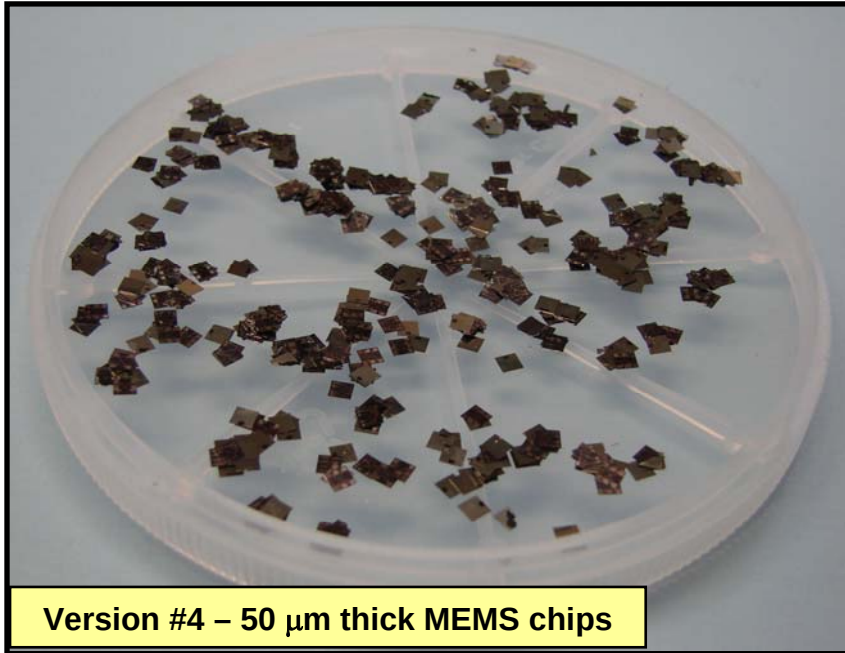
Wafer level gold bump bumping by electroplating process

Close-up view of gold bumps



Gold bumps of device chip

Figure SS10: Photos of version #4 & #5 MEMS strain-sensor modules



**Final Report - March 1, 2005 through April 30, 2010
MEMS for Rolling-Element Bearings Program (Proposal Number 48371-EG)**

Program: MEMS for Rolling-Element Bearings
Project: Rapid-Bonding/Packaging Technology for MEMS Piezoresistive Strain-Sensor Modules
R&D by: The Timken Company

Objectives

The main objective of this project was to develop means of rapidly bonding MEMS strain-sensor modules to steel structures and electrically connecting them to signal-conditioning electronics for low-cost, high-production-volume applications. To this end, the scope of this project consisted of the following tasks:

1. Development of a process for rapidly bonding MEMS strain-sensor modules to steel.
2. Development of flexible-circuit boards for electrically connecting MEMS strain-sensor modules to signal-conditioning electronic cables.
3. Development of a thermo-ultrasonic flip-chip bond process for bonding MEMS strain-sensor modules to flexible-circuit boards.
4. Development of a high-temperature back-fill packaging process for strengthening the bond of MEMS strain-sensor modules to flexible-circuit boards and environmentally protecting the MEMS strain-sensor modules bonded to steel structures.

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Approach

Investigation of various eutectic alloys and their properties led to the selection of Au/Sn eutectic alloy as the bonding layer followed with the development of a wafer-level deposition process to pre-coat Au/Sn eutectic alloys on the backside of the MEMS chips with accurate film thicknesses and patterns, and the development of a process to pre-coat steel substrates with a Ni/Au layer that acts as a bond agent. A wafer-level gold bumping process was used to place uniform-shaped gold bumps on the MEMS chip solder pads and a thermo-ultrasonic bonding flip-chip technique was developed to form the bond between the MEMS strain-sensor module and the flexible-circuit board. The main advantages of this approach, when compared to other technologies, were lower cost and enhanced reliability. Also a flexible-circuit board and a high-temperature back-fill packaging process were developed for the robust connection of MEMS strain-sensor modules to signal-conditioning electronics for low-cost, high-production-volume applications.

Significance

Rolling-element bearings are vital components of power-transmission devices. Bearings are precision devices that come in many shapes and sizes, and are responsible for carrying loads across rotational interfaces. They provide low-loss rotational motion about a principal axis, critical structural support, and load-carrying capability. Demanding power transmission applications such as transmissions, engines, gearboxes, wheels, and drivetrains rely on rolling-element bearings. Bearing failures are among the most costly and troublesome forms of breakdowns on mission critical machines. A failed bearing causes extended downtime and high repair costs, particularly when secondary machine damage occurs. Monitoring bearing operating characteristics such as load, temperature, and vibration can provide benefits useful to many defense, industrial, and commercial applications including the following:

- Insight into the health of a system
- Process/operation control
- Overload protection
- Bearing setting and alignment control

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Strain sensors are critical components for the measurement of loads in bearings and structures. Strain measurement provides a powerful indication of the structure's condition, not only for maintenance and safety purposes, but also for evaluation of structure health in applications. There is an increasing need for miniaturized, highly sensitive strain sensors for industrial and military applications such as in aircraft, bridges, dams, tunnels, monuments, buildings, elevators, presses, machine tools, cranes, aerial platforms, agricultural machines, and other machinery. When compared to strain sensors made with other technologies, MEMS strain sensors based on piezoresistive silicon gauges are very rugged, sensitive, and high-bandwidth devices. Techniques to rapidly bond MEMS strain-sensor modules to application substrates in high-volume-production applications are a key to great performance and low cost. These bonds must be strong and stiff enough to transfer the strain effectively from the steel structure, through the sensor's silicon base, to the transduction region of the sensor. Additionally, these bonds must last for long periods (greater than 10 years) in relatively harsh environments such as large temperature ranges and exposure to oil, grease, gasoline, and water. For these reasons, development of a bonding method based on the use of eutectic alloys and induction heating was pursued that provides many advantages over other bonding methods such as adhesives. For instance, induction heating is ideal for in-line production processes due to its ability to produce repeatable, rapid (under 10 seconds), and accurate heating cycles.

Accomplishments

1. Development of a process for rapidly bonding MEMS strain-sensor modules to steel by induction heating:

A eutectic-alloy bonding process with induction heating was sought for rapidly bonding MEMS strain-sensor modules to steel substrates (Figure RB1). Several eutectic alloys were investigated for use as the bond layer between the MEMS strain-sensor module and steel. Table RB-1 summarizes the characteristics of six eutectic alloys from which S-Bond 220M and Au/Sn were identified as the most suitable alloys. S-Bond 220M does not require pre-metallization, which may significantly lower the process cost, however, it does require the development of an ultrasonic wafer-level solder-coating system. Au/Sn on the other hand, can be coated at the wafer and chip level with better available processes such as electroplating or sputtering using room temperature deposition. However, it requires pre-metallization (Ti/Ni/Au) and an inert environment for joining surfaces, which may add additional cost in high-volume production. During the first development phase, S-Bond 220M was successfully coated onto steel substrates and silicon samples. However, the coating thickness significantly affected strain transmission which led to the development of a coating process that precisely controls the eutectic alloy thickness. The second development phase focused on the Au/Sn eutectic alloy that supports wafer-level coating with precise film thicknesses and wafer backside film patterning.

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Its mechanical properties are summarized as follows:

1. Joining temperature: 280°C
2. Excellent bonding strength: 40 ksi
3. Excellent corrosion resistance
4. High fatigue resistance
5. Good creep resistance
6. Coating at both wafer level and chip level (pre-form) at room temperature deposition
7. Joining surface pre-metallization (Ti/Ni/Au) is required

Proper eutectic bonding requires accurate heat generation and control. The effects of various electromagnetic parameters upon the heat generation on a steel beam by an induction heating system were studied using both FEA simulations and conducted test measurements as illustrated in Figure RB2. An FEA model was generated using a magnetic field frequency of 400 kHz, a 2-turn induction heating coil made from a 3 mm diameter wire, and a coil current of 80 Amperes. The obtained results indicated that the bonding interface temperature would rise to 278°C in about 6.2 seconds. An enhanced 3 kW Lepel induction heating system (Figure RB3) was used for the heat generation with specially designed water-cool induction heating coils. Figure RB4 shows the two coil designs developed specifically for this project, a 2-turn Pancake Induction Coil and a 3-turn Cone-Shaped Induction Coil. The effect of their design upon the heat generation on a steel beam was evaluated by the temperature distribution measured with a set of thermocouples placed at specific locations along the steel beam (Figure RB5).

Surface cleanliness plays an important role in coating processes for good adhesion. Investigation was made on the effect the cleanliness of silicon wafer backside had on the Au/Sn alloy film coating. A design of experiments was conducted to identify the nature of the chemical residue created on the backside of the wafer after the KOH etch. The results showed a strong correlation between the contamination of the substrate and pull strength values. To improve the cleanliness of the bonding surfaces, the bonding substrates were cleaned in an acetone and alcohol ultrasonic bath for 15 minutes. Surface preparation such as pre-metallization is another key parameter for bonding the strain-sensor module to steel. An electroplating process was also developed to coat inter-metallic layers of Ni/Au on stainless-steel surfaces (Figure RB6). In an electroplating process, the following factors affect the coating quality:

- Surface preparation
- Activation time and voltage
- Application technique
- Condition of plating tools and chemicals

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The applied electroplating process was developed based on Design of Experiments methodologies where variations of the process parameters were implemented, evaluated and optimized in experimental test runs. The process was optimized for coating inter-metallic layers of Ni/Au onto the bonding areas of four-point bending stainless steel beams, uniform-strain beams, and displacement sensor steel substrates (Figure RB7). For the application of a Ni/Au coating over small surface areas on a substrate, instead of dipping the entire substrate inside the electroplating solution, a brush plating technique was used where the electroplating solution was brushed over the substrate surface by dipping one of the system's electrodes inside the electroplating solution and then brushing the substrate surface with the electrode tip.

Applied pressure and bonding temperature are crucial parameters for good bonds. If the temperature is not uniform, the viscosity of the melt will vary. This can create some solid and some liquid areas on the backside of the device, which can cause the device to crack under the applied bonding force as bending moments develop in regions with varying compliance. Special fixtures were designed that align the device-bonding interface to the steel substrate and apply a calibrated bonding force using Pyrex glass chips as weights. An improved loading mechanism was also developed that holds the steel substrate in place during bonding and a small mechanical retainer that can be bolted to the base and provide a load to the device (Figure RB8). Good contact area between the strain-sensor module and the steel substrate improves the heat transfer from the steel substrate to strain-sensor module. Grain-boundary reactions can play a major role in the success or failure of the bonds. Sometimes microvoids form in the eutectic microstructure after eutectic bonds are cooled. These voids may occur when one element diffuses more quickly than the other and the lattice sites left behind are empty. In some cases, the vacancies cluster and lead to microvoiding. In most cases, this can be overcome by adjusting the cooling rates and the amount of heating. In addition, to prevent the bonding surfaces from oxidizing and weakening the bonding strength, a chamber was fabricated to maintain the bonding surfaces in an inert gas atmosphere, such as 100% argon gas atmosphere (Figure RB9). The chamber can be purged with 100% argon gas and under the established nominal flow rate, the oxygen level near the bonding area is reduced to 0.001% in 15 minutes. A series of experimental bonding trials led to the following induction heating process for optimum bonding results (Figure RB10):

1. Apply a heating rate of 50°C per minute with no dwell-time to raise the temperature of MEMS chip and steel substrate up to the peak temperature of 320°C.
2. Keep heating time duration above the eutectic temperature of 280°C for 2-3 minutes following a bell-shape temperature profile without plateau at peak value.
3. Apply a cooling rate of 50°C per minute or less to prevent any component thermal stress.
4. Use oxygen-probe to maintain oxygen content of applied argon gas below 20 ppm.

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The above processes were combined together to form a eutectic bonding process by induction heating for bonding MEMS strain-sensor modules onto steel substrates. The developed bonding procedure was as follows:

1. Apply inter-metallic layers (Ni/Au) onto steel substrate contact surfaces
2. Setup the appropriate heating temperature profile
3. Purge argon gas into the well-sealed chamber for 2 minutes (Oxygen detector should show 0-2% oxygen remaining after 2 minutes of argon purging)
4. Hold MEMS sensor and steel substrate in place inside the inert gas atmosphere
5. Set a 1 cm air-gap between induction heating coil and MEMS sensor surface
6. Use Lepel's 3KW induction heating system (set to 23% power) to heat the MEMS sensor and steel substrate to the pre-selected eutectic alloy melting temperature and then cool down the bonded samples at the pre-selected cooling rate for the formation of a strong eutectic bond

The above bonding procedure was used to bond MEMS strain-sensor modules onto four-point bending stainless steel beams, displacement sensor substrates, and thin-beam load cell substrates (Figure RB11).

2. Development of flexible-circuit boards:

Due to the small size of MEMS strain-sensor modules, flexible-circuit boards were developed to electrically connect them with the signal-conditioning electronic cables. The flexible-circuit boards had to have copper traces for interconnection and bonding pads that match those of the MEMS strain-sensor module. A thermo-ultrasonic flip-chip bond process was selected for bonding the MEMS strain-sensor modules onto the flexible-circuit boards. The developed flexible-circuit boards had to also withstand the 350°C temperature of post-process assembly for 30 minutes. Several materials were investigated and DuPont AP 8555 polyimide was selected as the preferred substrate material. Three generations of flexible-circuit boards were developed as shown in Figure RB12 with a Ni/Au coating placed on their copper traces to prevent oxidation, and a 1.27 μm thick soft gold layer placed on their bonding pads to function as bonding agent. In order to verify the temperature durability of adhesive used for the coverlay on the copper trace, three design variations were made in the second generation boards, in terms of their coverlay layer configuration. Design A had a coverlay layer on its entire surface except over its bonding pads, design B had a coverlay layer on half of its surface closest to the induction heating coil side, and design C had no coverlay layer on its surface. Based on conducted experiments, design A was chosen as the preferred design. The third generation flexible-circuit boards, had a design A coverlay configuration and were produced into two groups, one with 0.127 mm thickness and 1/2 oz copper, and the other with 0.051 mm thickness and 1/2 oz copper. Their design had several slots placed at key locations that function as entrance points for a back-filling adhesive.

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3. Development of thermo-ultrasonic flip-chip bond process:

Compared with other flip-chip bonding methods, ultrasonic bonding offers the advantages of lower electrical resistance and stronger mechanical retention. This is because of the metallic bond created between the gold bumps and the gold-plated pads on the flexible-circuit substrate. Ultrasonic bonding also requires less down force. This reduces deformation and cracking of flexible-circuit pads. With ultrasonic bonding it is not necessary to control solder wetting or wash away any kind of soldering flux. It is also superior to the solder bump methods in that it uses lower temperatures. Ultrasonic bonds can be created at room temperature, an important consideration given that flexible-circuit boards can be harmed by excessive heat. The small dimensional deviation of flip-chip circuits at lower temperatures also helps realize fine pitch bonding with high accuracy. In the past, the ultrasonic flip-chip bonding method was only applied to small dies with a few pins. This is because of the equipment used – a modified wire bonding machine that lacked effective vibration energy and caused harmful vertical vibrations. For this development, state-of-the-art ultrasonic bonding equipment from Finetech was found capable for the large size dies and did not exhibit these problems.

Figure RB13 shows the flip-chip bonding assembly for the strain-sensor module. For accurate alignment to the bond pads on the substrate, an upward-looking camera identifies the bumps on the die. The die is then placed on the substrate. Leveraging the flip-chip bumping technology, the device is ultrasonically heated and pressed, forming the electrical and mechanical interconnections. A thermo-ultrasonic flip-chip bonder was chosen based on its alignment accuracy and throughput capacities. The most important advantage in this application was that the temperature for the flip-chip bonding is just about 150°C, which is much below the device backside Au/Sn alloy reflow or melting temperature point. Variables, such as power, time, bonding pads, positioning, and temperature could be the root causes of poor bonding quality. Using Design of Experiments methodologies, successful bonding parameter were established (Figure RB14) taking into consideration the following experimental observations:

- The optimum power setting was at 11 W for 2 seconds.
- Discovered that there was a 80°C difference between the heating surface displayed temperature and its actual temperature. Therefore, to achieve a 150°C bonding temperature the setting had to be at 235°C for 60 seconds.
- Determined that 11 N load for the entire bonding cycle provided good bonding results.
- Determined that proper bonding was achieved by alignment for the slots on the chip and bonding station.

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4. Development of high-temperature back-fill packaging process:

The objective of high-temperature back-fill packaging process was to increase the bonding strength of MEMS strain-sensor module to flexible-circuit boards, to increase the bonding strength of flexible-circuit board to steel substrates, and to encapsulate and protect the MEMS strain-sensor module from its implementation environment. In a common flip-chip bonding operation, bonding of a device is followed by a back-fill operation using adhesives for an increase in bonding strength. The challenge in this application was to find an adhesive that will survive the 320°C induction-heating temperature in the rapid bonding process. Several adhesives were investigated and Duralco™ 4460 (Figure RB15) was selected as the preferred back-fill material. Duralco™ 4460 is a two-part resin used for low-viscosity potting, coating and impregnation. Its operating temperature is 315°C and its curing instructions are as follows:

- Mix 100 parts of resin to 80 parts of hardener by weight
- Mix thoroughly
- Cure for 4 hrs @ 120°C
- For optimum properties, cure an additional 1-2 hrs @ 175°C
- For use in severe environments, post-cure 16 hrs @ 230°C

A modified version of the above curing process that produced stronger bonds was used in this project as follows:

- Mix 100 parts of resin to 80 parts of hardener by weight
- Mix thoroughly
- Cure for 6 hrs @ 120°C
- Post-cure for 4 hrs @ 175°C

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5. Bonding MEMS strain-sensor modules on application structures:

A special setup was developed to allow reliable bonding of MEMS strain-sensor modules and their flexible-circuit boards on steel substrates with the induction heating process. In this setup, a pancake-shaped induction coil was used with a high-temperature plastic rod passing through the coil and resting upon the flexible-circuit board with the MEMS chip directly underneath and against the steel substrate (Figure RB16). A small metal weight was also placed at the top end of the plastic rod to provide a constant small downward holding force on the flexible-circuit board and MEMS chip. Figure RB17 shows several MEMS chips w/ flexible-circuit boards bonded on steel substrates and back-filled with the high-temperature Duralco™ 4460 adhesive.

As a general rule, to minimize the effect of light on the piezoresistive elements in the MEMS strain-sensor module, bonding of MEMS strain-sensor modules on application structures requires the placement of a thin UV silicon coating over the MEMS module and painting of the cured UV silicon coating with permanent black paint.

Conclusions:

The above developmental efforts led to the following four processes for the rapid bonding/packaging of MEMS strain-sensor modules to steel structures:

1. Development of a process for rapidly bonding MEMS strain-sensor modules to steel.
2. Development of flexible-circuit boards for electrically connecting MEMS strain-sensor modules to signal-conditioning electronic cables.
3. Development of a thermo-ultrasonic flip-chip bond process for bonding MEMS strain-sensor modules to flexible-circuit boards.
4. Development of a high-temperature back-fill packaging process for strengthening the bond of MEMS strain-sensor modules to flexible-circuit boards and environmentally protecting the MEMS strain-sensor modules bonded to steel structures.

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Technology Transfer

During the MFREB program duration, several progress reports and program presentations were presented to members of ARO and ARL as follows:

1. August 31, 2005 – Annual progress report
2. September 9, 2005 – Program presentation
3. September 30, 2005– Interim progress report
4. August 14, 2006 – Interim progress report
5. August 31, 2006 – Annual progress report
6. September 22, 2006 – Program presentation
7. March 15, 2007 – Interim progress report
8. August 31, 2007 – Annual progress report
9. June 30, 2008 – Program presentation
10. August 31, 2008 – Annual progress report
11. December 31, 2008 – Interim progress report
12. March 26, 2009 – Program presentation
13. April 30, 2009 – Interim progress report
14. August 31, 2009 – Annual progress report
15. July 30, 2010 – Final program presentation
16. July 30, 2010 – Final program report

A prototype Micro-Strain/Displacement Sensor made from metal-foil strain gauge was displayed on a Toolcat™ (Utility Work Machine) at the SAE Commercial Vehicle Engineering Congress and Exhibition from October 30 to November 1, 2007 in Rosemount, IL.

A prototype Micro-Strain/Displacement Sensor made from metal-foil strain gauge was displayed on a Toolcat™ (Utility Work Machine) at the SAE World Congress and Exhibition from April 14 to April 17, 2008 in Detroit, MI.

A prototype MEMS Micro-Strain/Displacement Sensor made from MEMS piezoresistive strain-sensor module was displayed on a force-sensing beam at the SAE World Congress and Exhibition from April 14 to April 17, 2008 in Detroit, MI.

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In January 2008, the potential application of MEMS strain sensors and displacement sensors to bridge usage and health monitoring was discussed with representatives of the Army's Engineering Research and Development Center (ERDC-GSL-MS and ERDC-GSL-MS).

In December 2008, a test was conducted to monitor the loads from traffic on a public bridge using several bolt-on displacement sensors made from MEMS piezoresistive strain-sensor modules. The conducted test included both wired and wireless hook-up configurations (using Timken's wireless StatusCheck[®] 2.4 system). An accompanying report was issued on April 30, 2009 describing details of the conducted test.

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Rapid-Bonding/Packaging Technology

**Developed under the
MEMS for Rolling-Element
Bearings Program**

July 30, 2010

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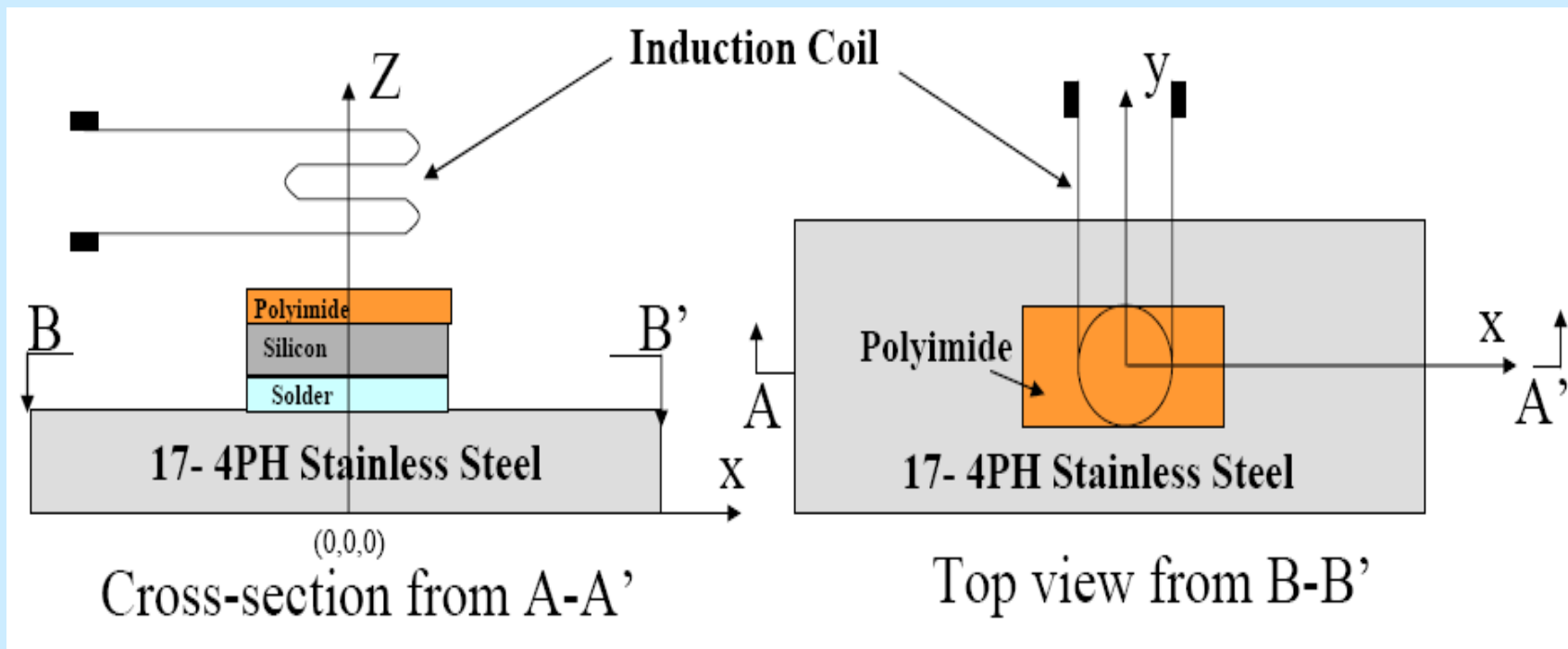
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Table RB-1: Characteristics of several eutectic alloys

Properties	Au/Sn		S-Bond 220M (Sn-Ti-Ag)	Sn3.5Ag0.5Cu UCB	Epoxy MB-610 CWRU	Dymax® 848 structure adhesive, CWRU
	Au(10)/Sn(90)	Au(80)/Sn(20)				
Joining Temperature (°C)	217	280	250-280	220	150	NA
TCE @ 20 °C (ppm/°C)	16	16	19	?	NA	NA
Tensile Strength (psi)	7280	40000	6000	5800	NA	1000
Shear Strength (psi)	7280	40000	6000	2700	NA	NA
Young's Modulus (GPa)	68	60	?	56	NA	NA
Corrosion resistance	excellent	excellent	excellent	excellent	limited	limited
Fatigue resistance	NA	high	NA	NA	NA	NA
Creep resistance	good	good	good	good	limited	limited
Intermetallization	Ni/Au	Ni/Au	prewetting	Ti/Cu	No need	No need
Joining atmosphere	inert gas or vacuum	inert gas or vacuum	joins in open air	joins in open air	joins in open air	joins in open air
Bonding time	15 second now, capable to seconds	15 second now, capable to seconds	15 second now, capable to seconds	5 second bonding only	1hr cure, post cure 1~2 hrs at 210 °C	30 seconds hand operation
Manufacturability	requires intermetallization	requires intermetallization	joins in open air, needs prewetting	joins in open air	joins in open air	joins in open air
Comment	high bonding strength	excellent bonding strength	Prewetting cost effective compared to preplating on steel	Preplating needed	Low cost, limited corrosion/fatigue/ creep resistance	Low cost, limited corrosion/fatigue/ creep resistance

Figure RB1: Bonding of MEMS sensor with Au / Sn eutectic alloy & induction heating

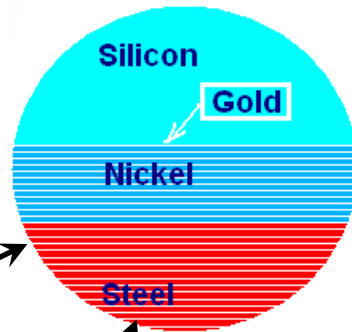


**Inductive heating rapidly bonds
MEMS strain sensor (with integral solder) to steel**

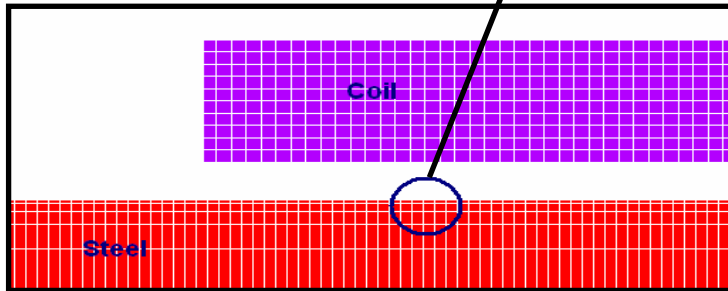
Figure RB2: FEA Modeling of induction heating process

Finite Element Model

Magnetic field frequency = 400 kHz
 Induction Heating Coil = 2 turns
 Current = 80 Amperes,
 Diameter of coil wire = 3mm



Enlarged picture
 of heating object
 layers



Conducted FEA work indicates that the above
 induction coil can heat the work piece to
 278°C in 6.2 seconds.

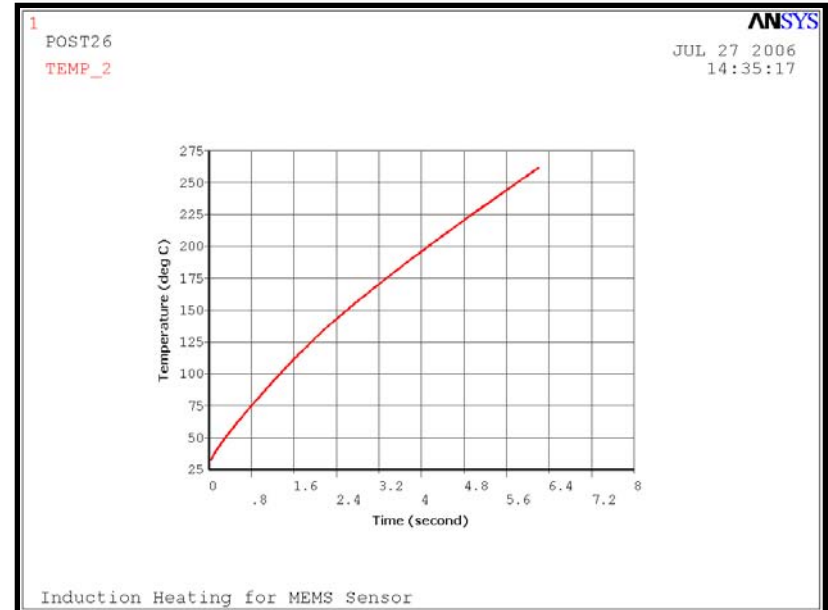
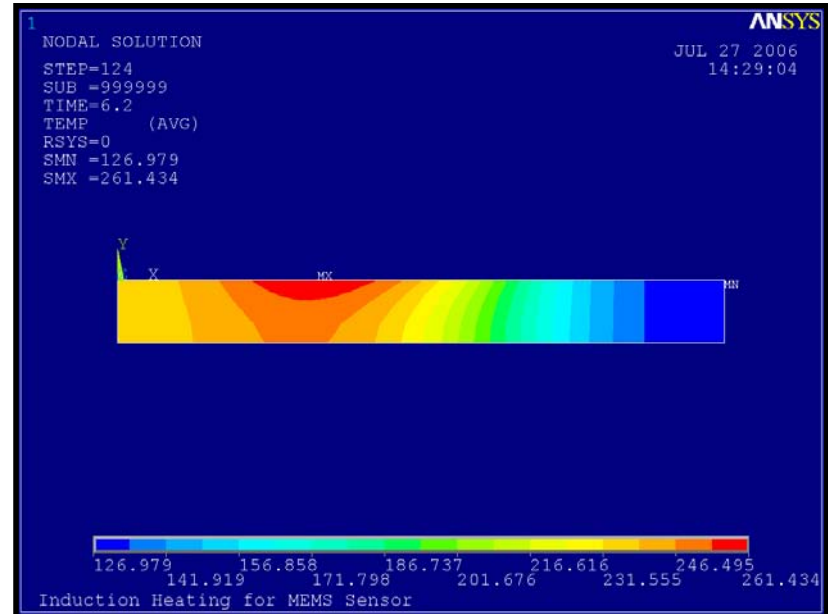
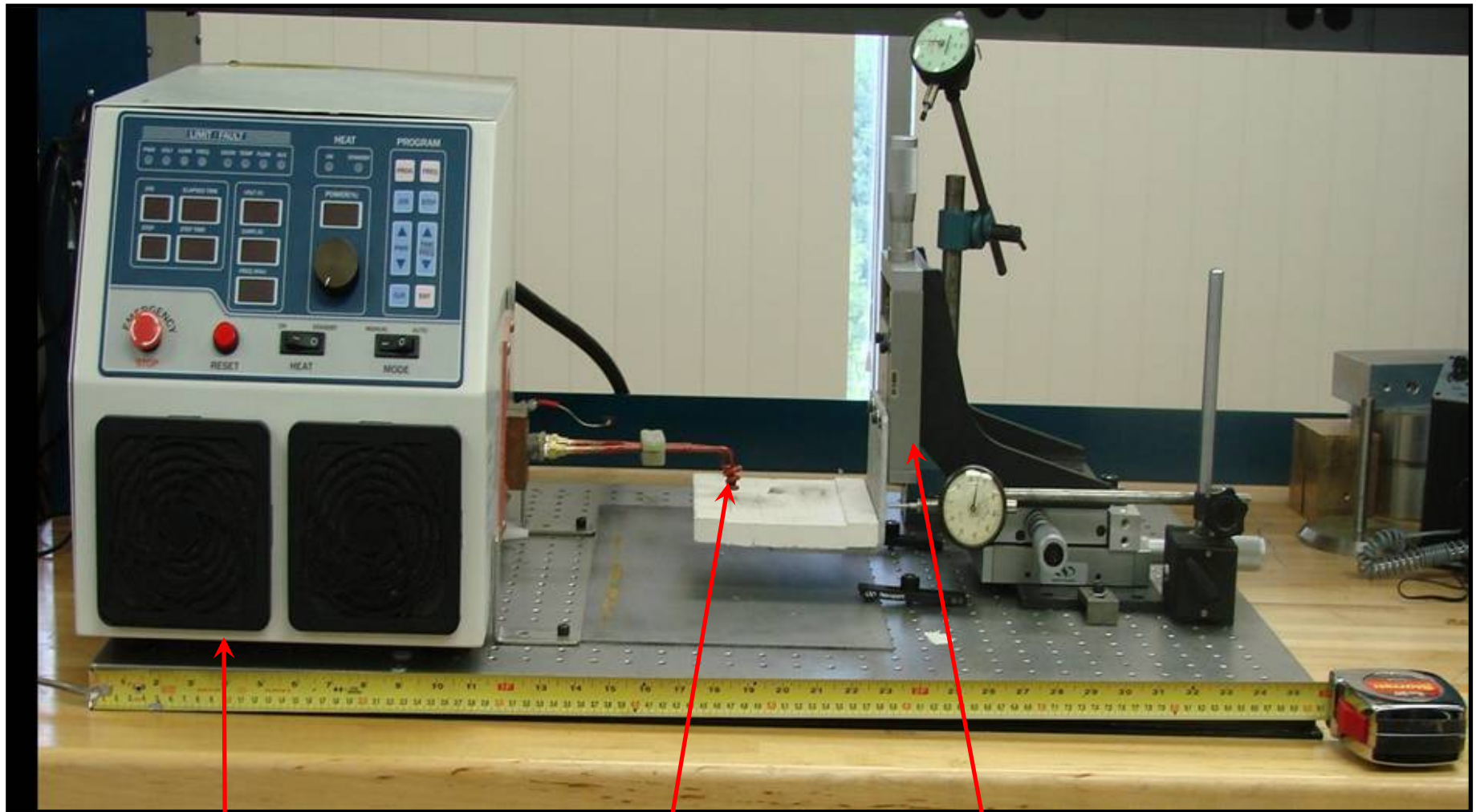


Figure RB3: Enhanced Lepel induction heating equipment



**Lepel 3 kW; 135-400 kHz
induction heating system**

**Induction
heating coil**

X-Y slide assembly

Figure RB4: Developed induction heating coils

2-turn pancake induction coil



3-turn cone-shaped induction coil

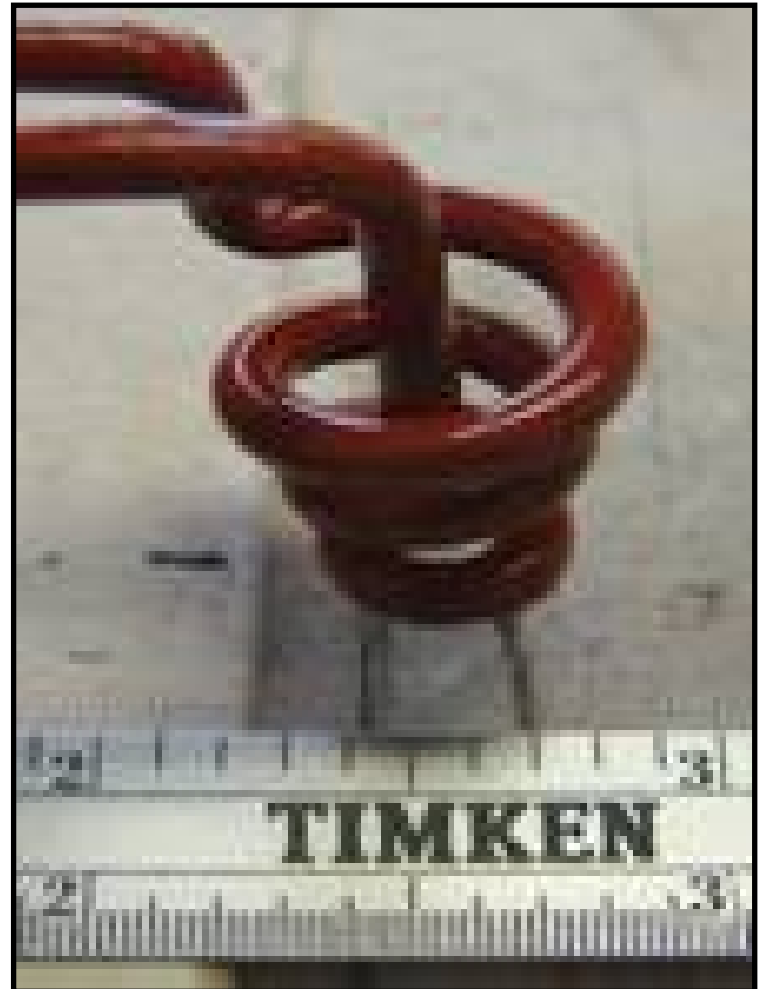
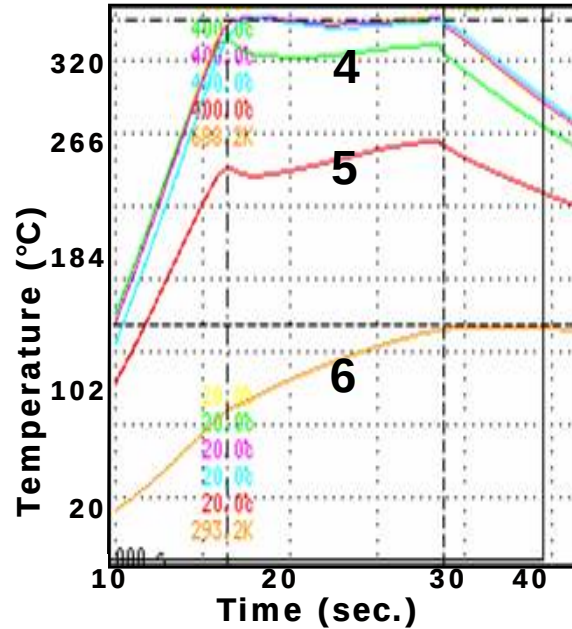


Figure RB5: Temperature distribution on steel beam induced by induction coils



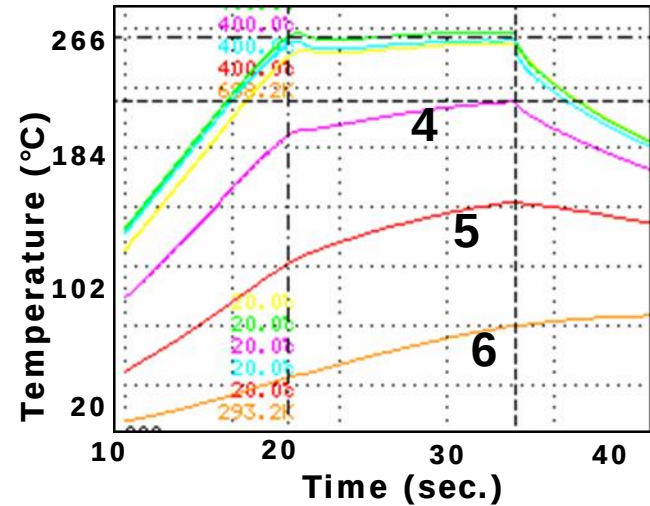
1-2-3



Temperature distribution of steel beam induced by a 2-turn pancake coil



1-2-3



Temperature distribution of steel beam induced by a 3-turn cone-shaped coil

Figure RB6: Pre-metallization of steel substrate with Ni/Au coating

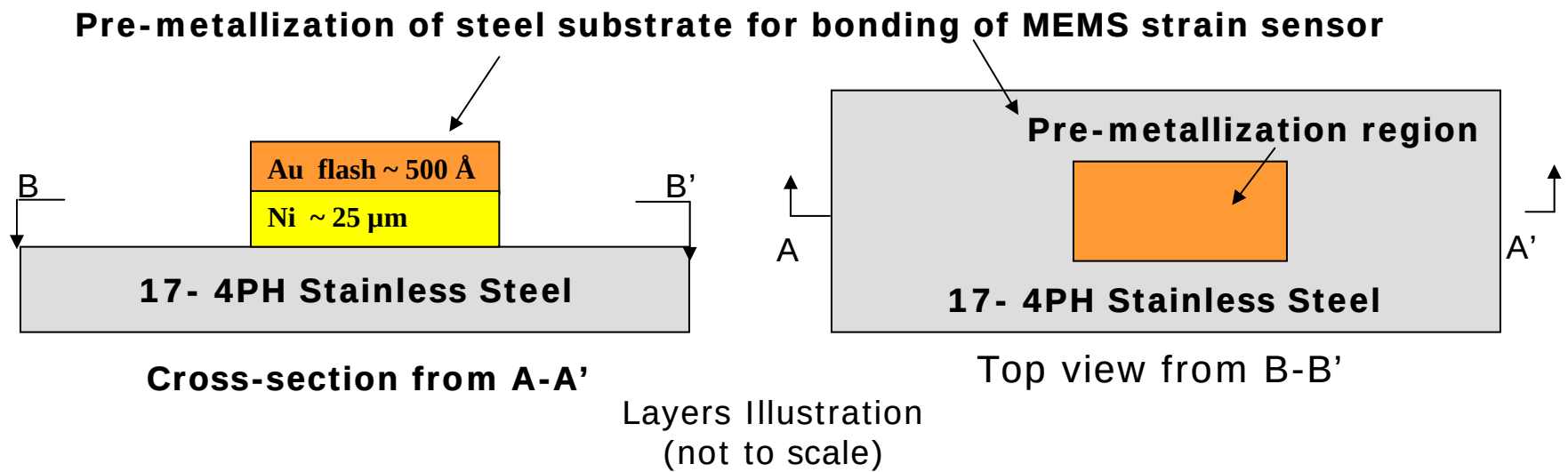
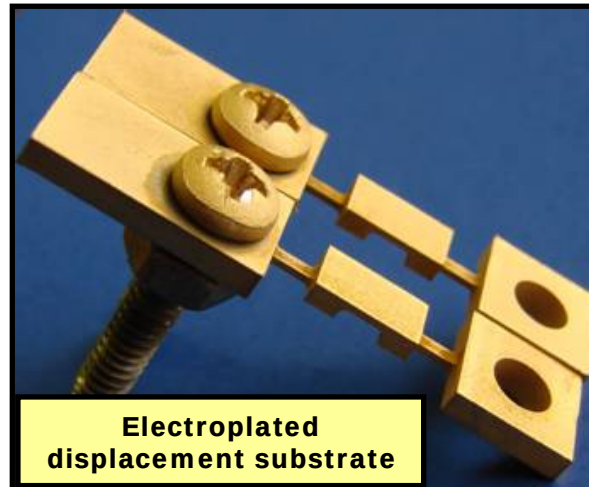
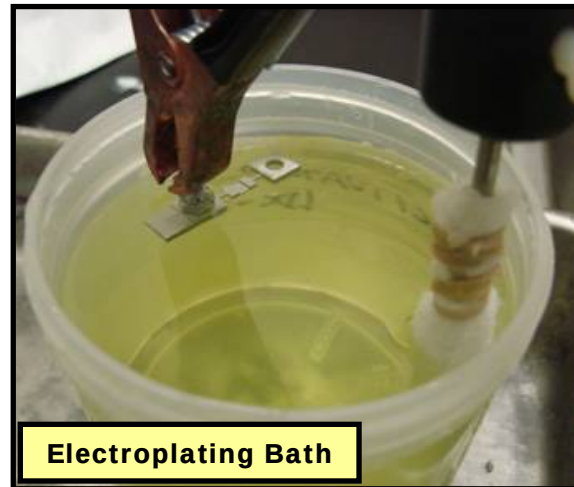


Figure RB7: Electroplating process for Ni/Au coating



**Electroplated
load-cell substrate**



**Electroplated four-point
bending beam substrate**

Figure RB8: Enhanced sample-holding tool at induction heating station

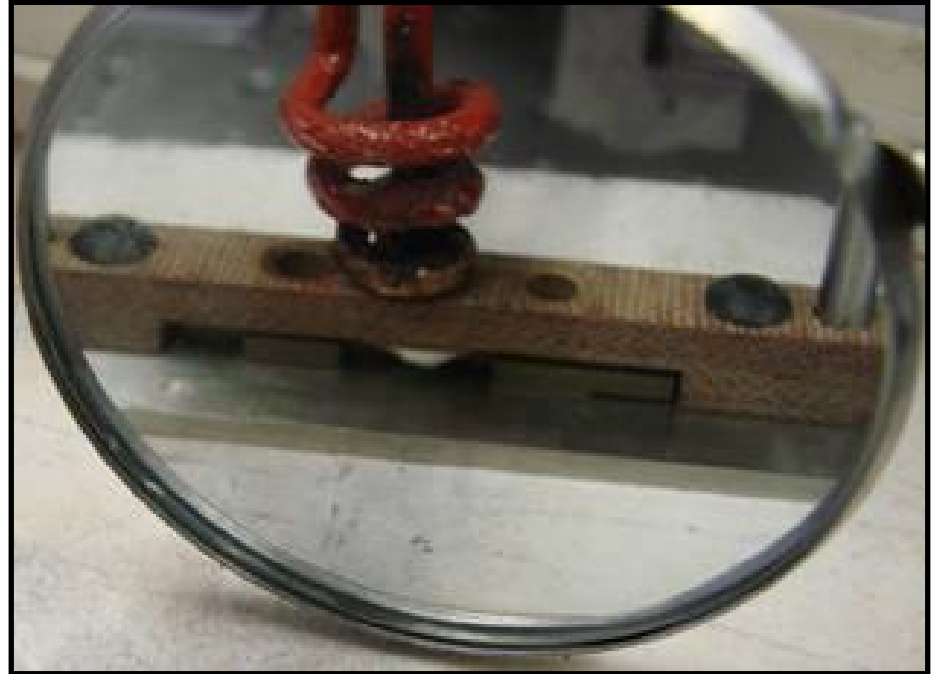
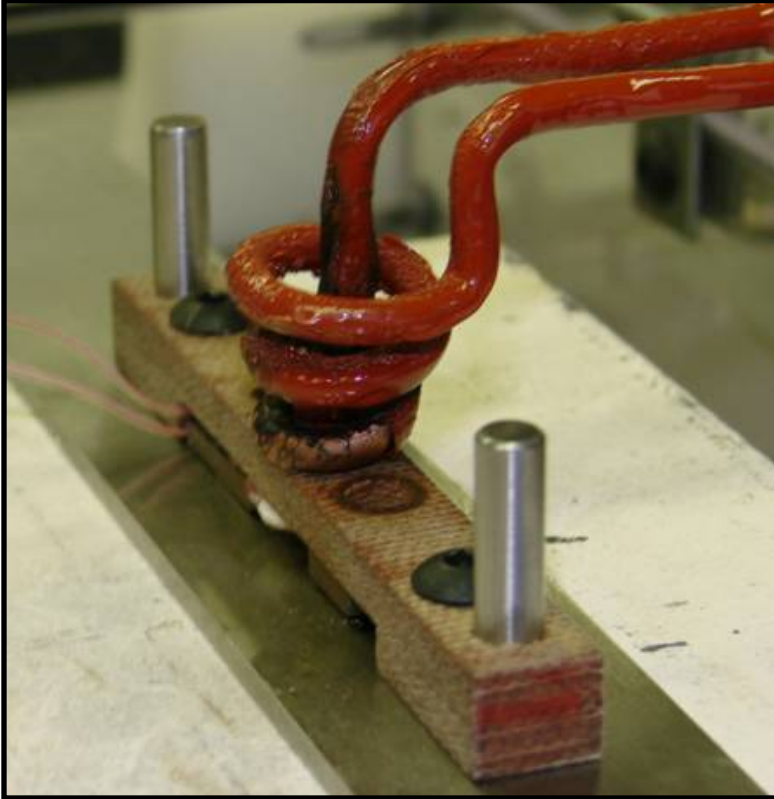


Figure RB9: Induction heating coil inside inert gas chamber to prevent oxidation

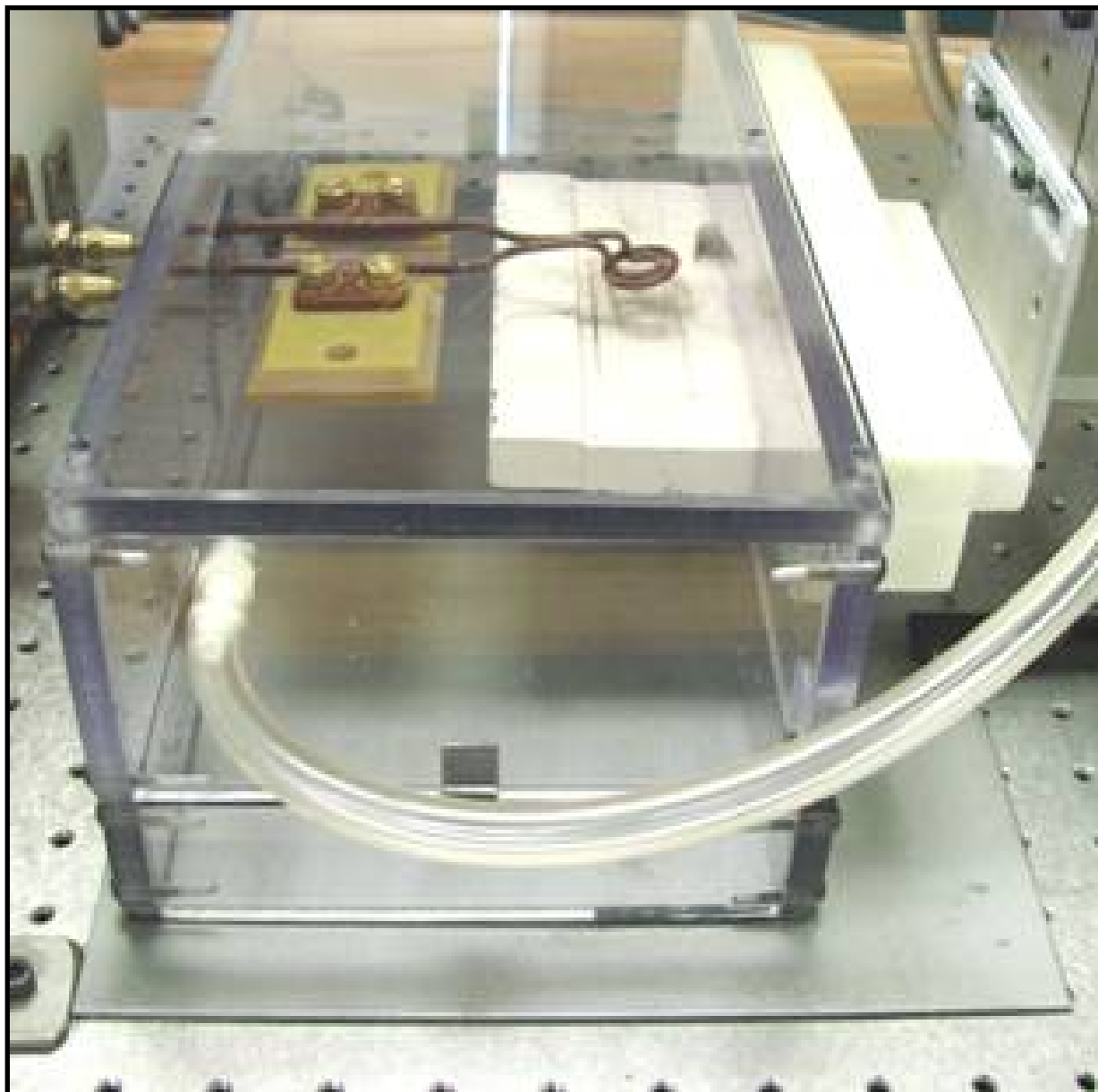


Figure RB10: Optimized induction heating profile

Induction Heating Process:

1. Apply a heating rate of 50°C per minute with no dwell-time to raise the temperature of MEMS chip and steel substrate up to the peak temperature of 320°C.
2. Keep heating time duration above the eutectic temperature of 280°C for 2-3 minutes following a bell-shape temperature profile without plateau at peak value.
3. Apply a cooling rate of 50°C per minute or less to prevent any component thermal stress.
4. Use oxygen-probe to maintain oxygen content of applied argon gas below 20ppm.

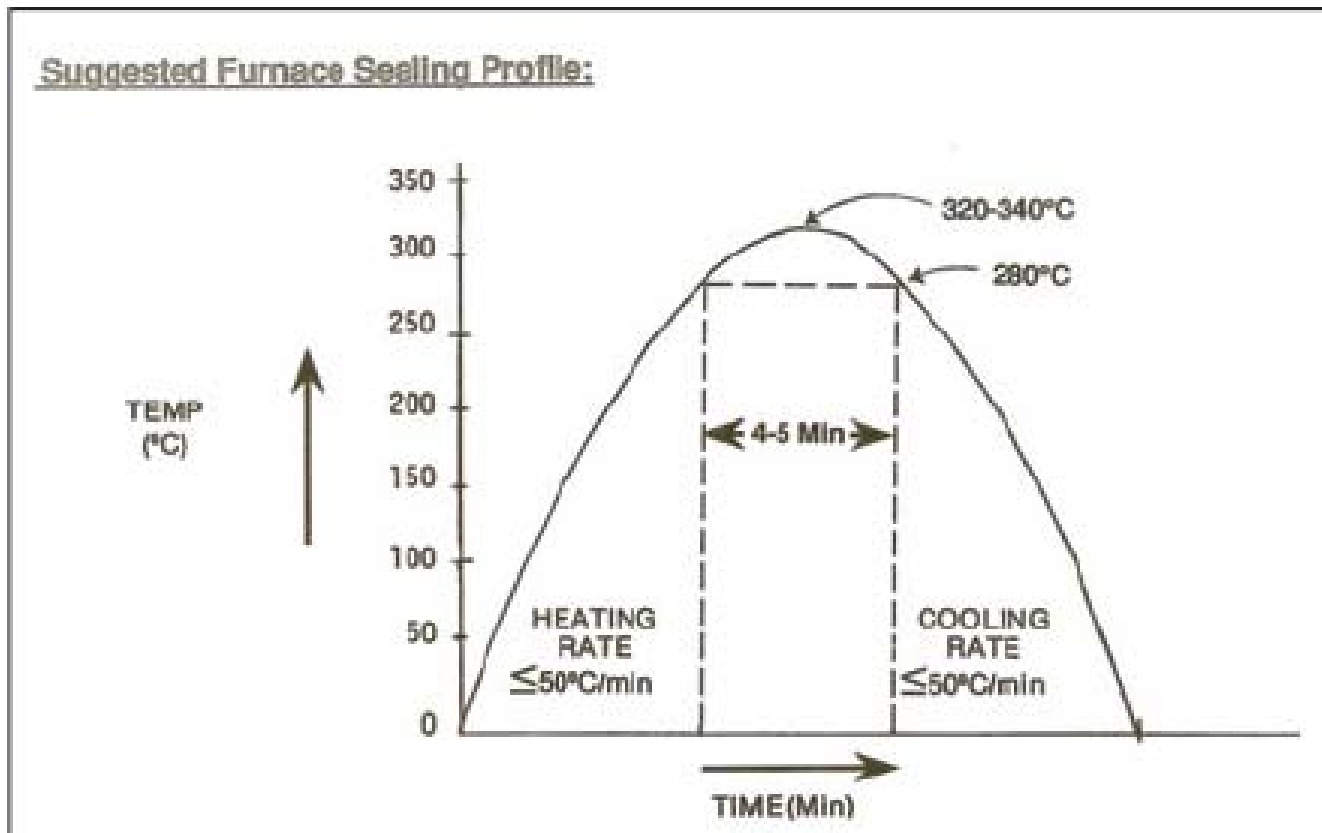


Figure BR11: MEMS piezoresistive strain sensors bonded to steel substrates

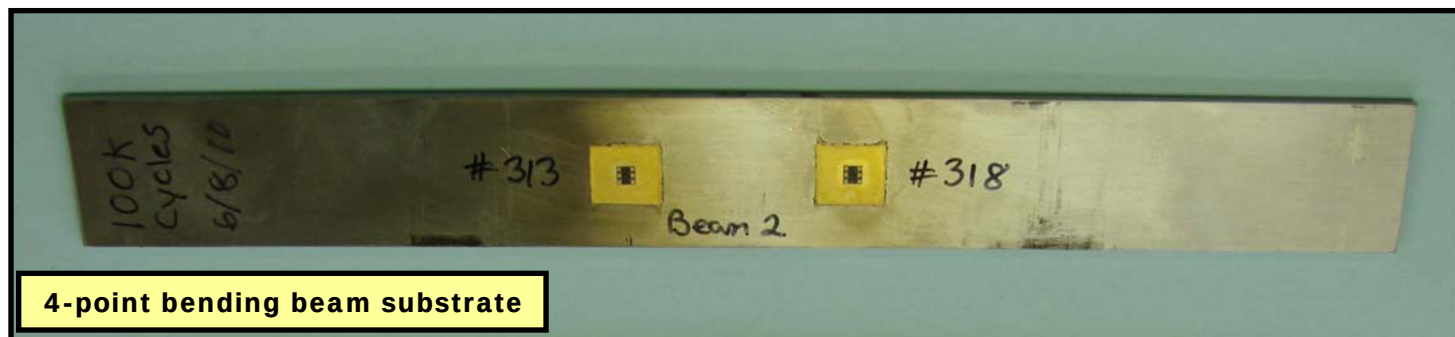
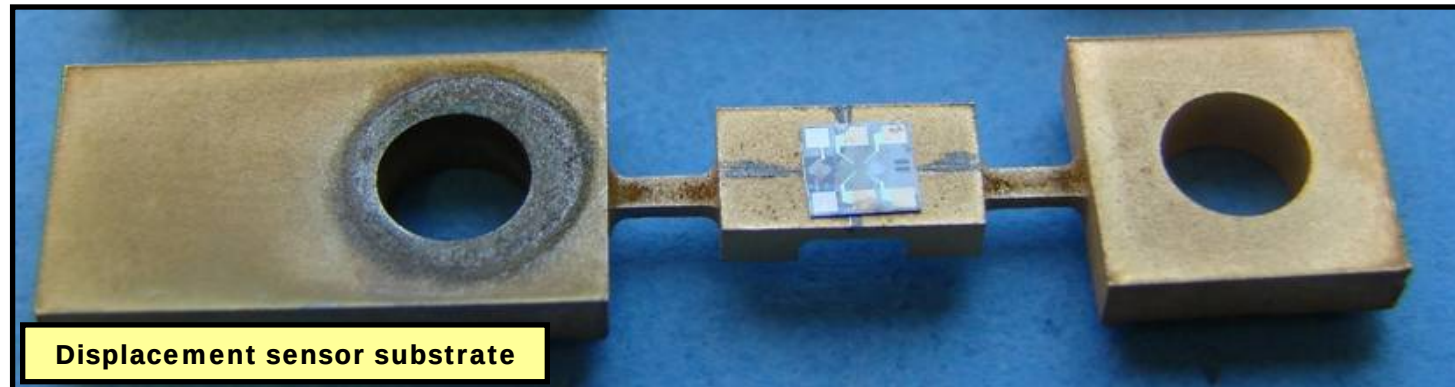
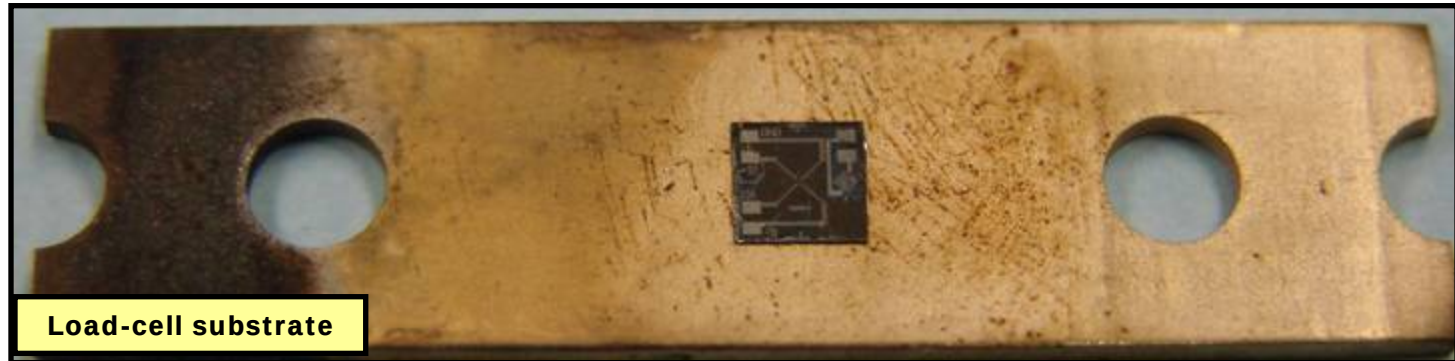
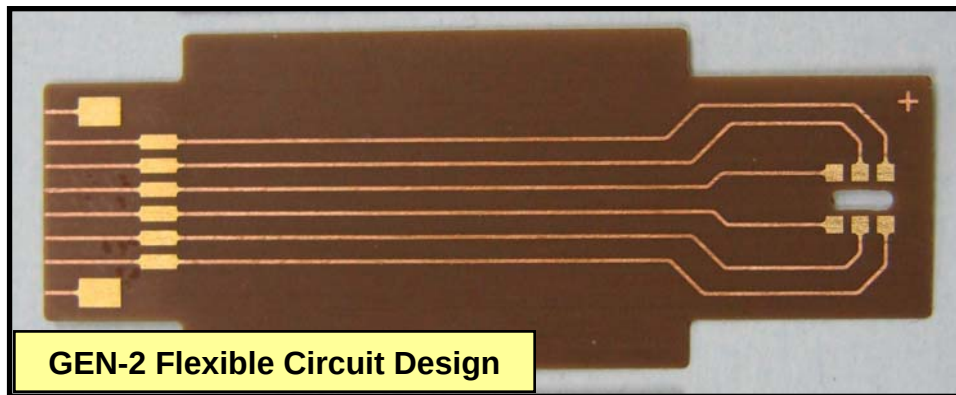
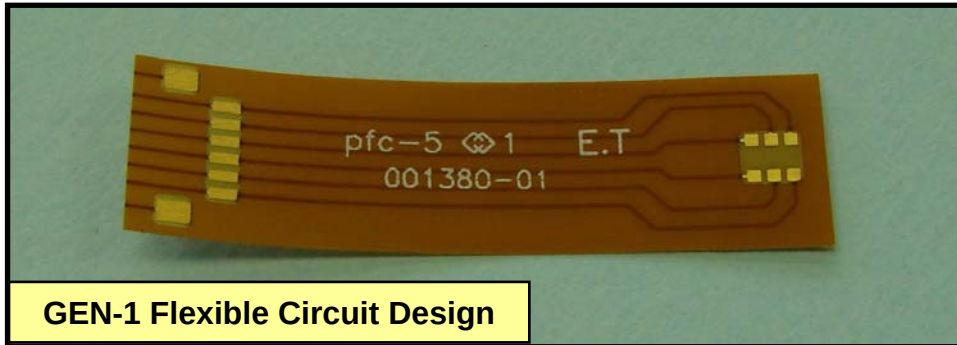
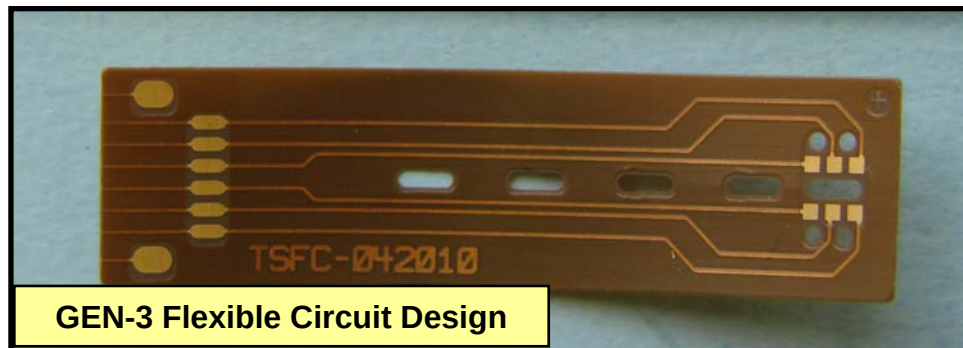


Figure RB12: Fabricated flexible-circuit board designs



Type A: Full Coating
Type B: Partial Coating
Type C: No Coating



Type A: 0.127 mm Thick
Type B: 0.051 mm Thick

Figure RB13: Thermo-Ultrasonic flip-chip bonding technique

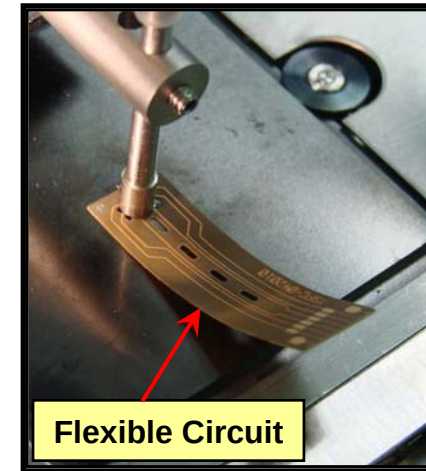
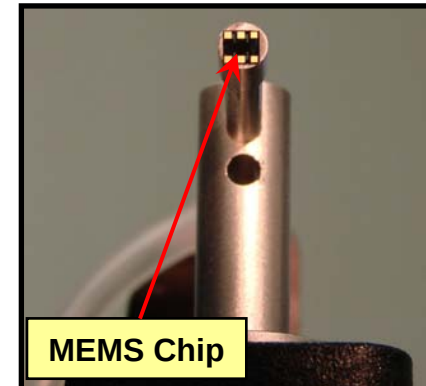
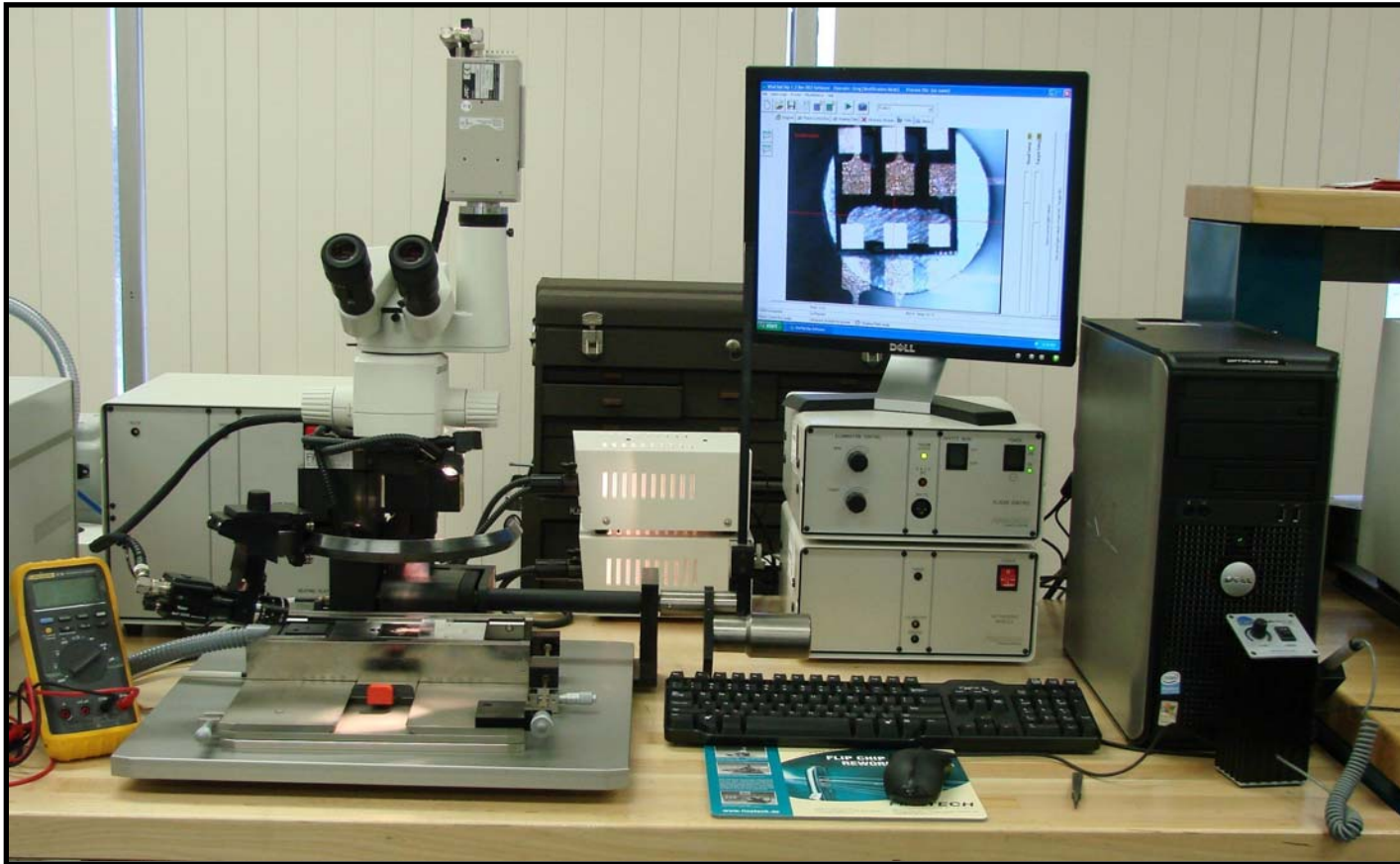


Figure RB14: Bonded Version #4 MEMS chips on flex-circuit boards

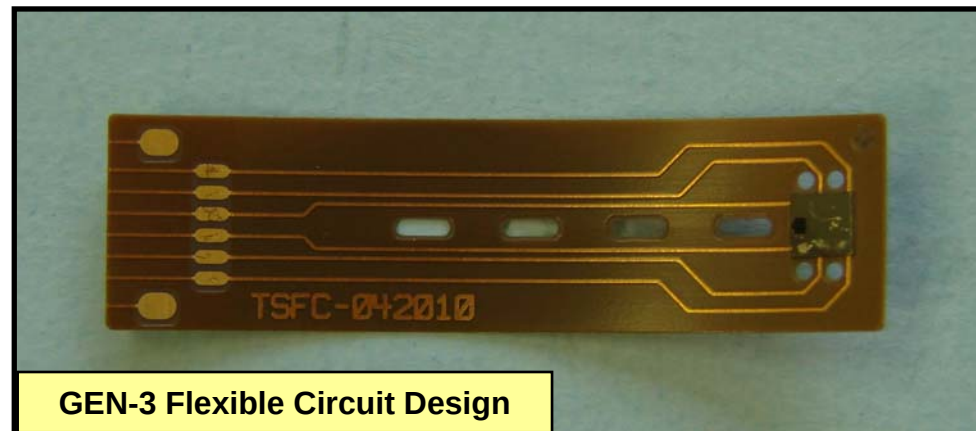
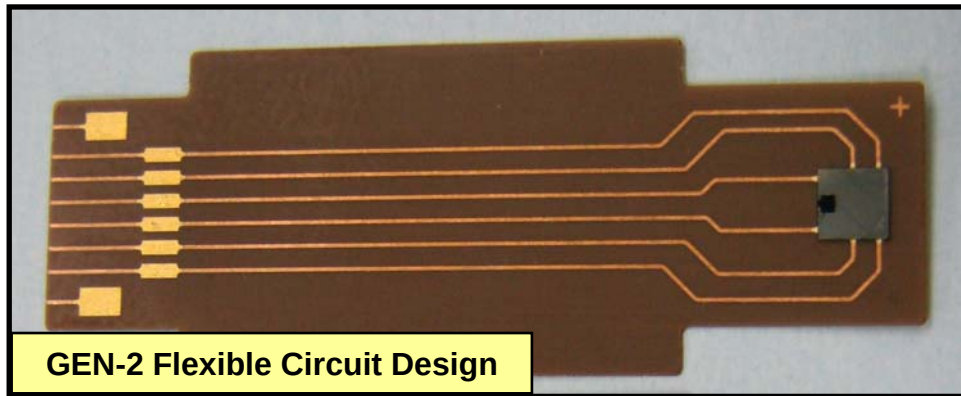


Figure RB15: Duralco™ 4460 high-temperature back-fill adhesive



Figure RB16: Setup for bonding MEMS chips w/ flexible-circuit on steel substrates

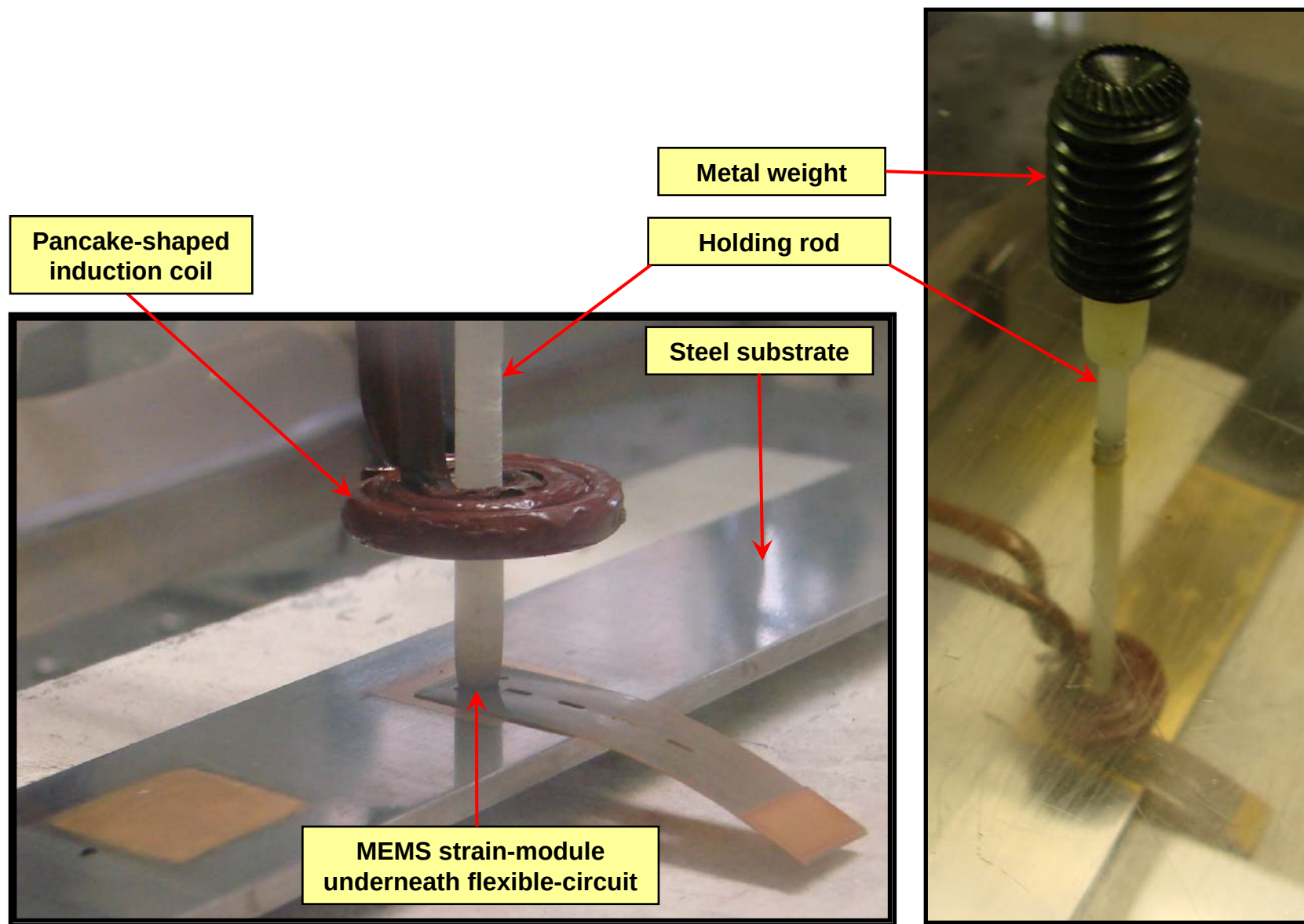
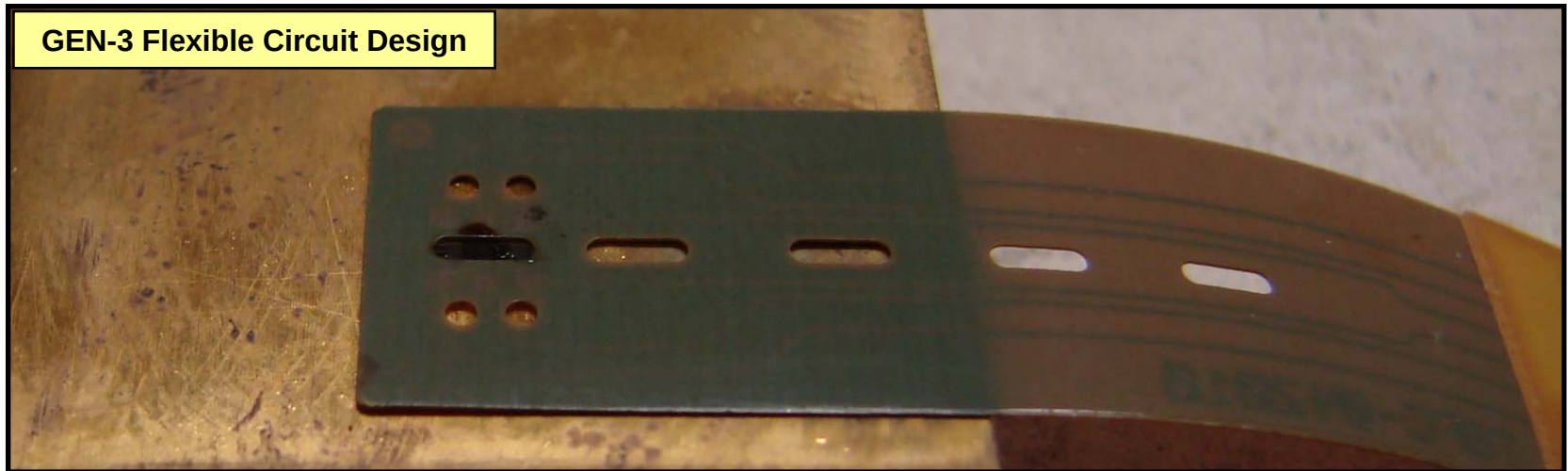
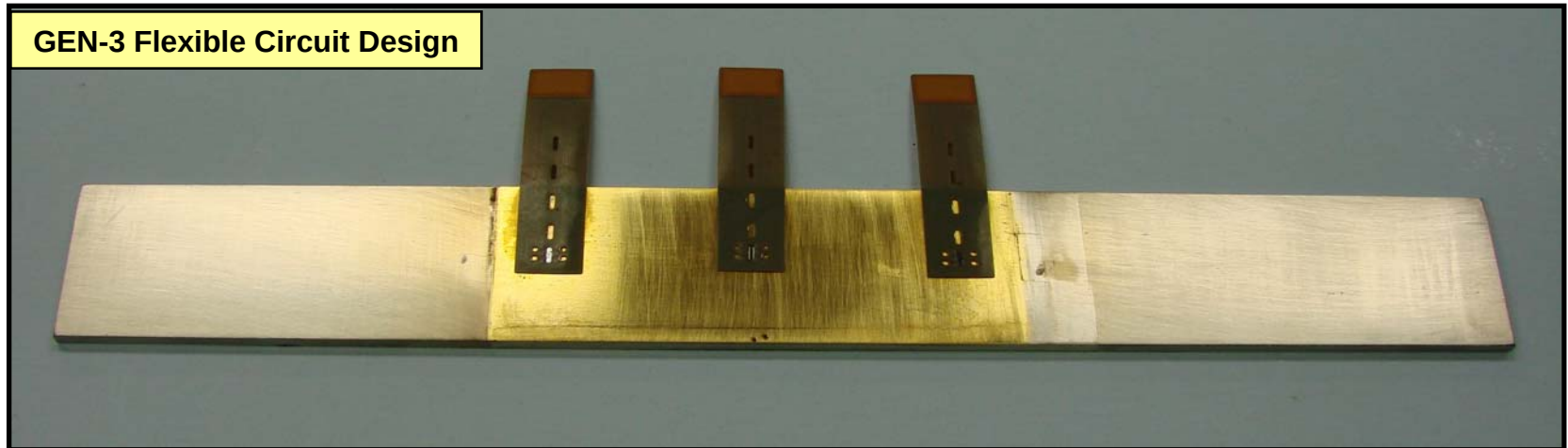


Figure RB17: MEMS chips w/ flex-circuit bonded on steel substrates & back-filled with high-temperature adhesive



Final Report - March 1, 2005 through April 30, 2010
MEMS for Rolling-Element Bearings Program (Proposal Number 48371-EG)

Program: MEMS for Rolling-Element Bearings
Project: MEMS Displacement Sensors to Bridge Gaps in Application Structures
R&D by: The Timken Company

Objectives

The main objective of this project was to develop a low-cost, very sensitive, rugged displacement sensor and associated electronics capable of measuring displacements in one direction across a gap or solid section in a structure for real-world applications. The displacement sensor includes features for its rapid attachment to and removal from application structures and its permanent installation on application structures.

Approach

A low-cost, very sensitive, and rugged Displacement Sensor and associated electronics were developed. The sensor system is capable of measuring displacements in one direction across a gap that can be many millimeters wide or solid section in an application structure. The displacement sensor consists of a MEMS strain-sensor module integrated inside a specially designed low-cost and rugged package with connecting cable and a "bolt-on" feature for rapid attachment to the application structure. The integrated MEMS strain-sensor module facilitates great performance through its high sensitivity, high accuracy, ruggedness, and temperature compensation capabilities and it provides temperature information to the end user. Novel use of anisotropic package stiffness facilitates the measurement of displacements in one desired direction (axial, x-direction) while minimizing the errors due to undesired applied displacements (in the y and z-directions) and rotations (about the x, y and z-directions). The sensor bolt-on feature allows quick installation in high-volume production lines and in the field for low installation and maintenance cost. The sensor package allows also permanent installation in an application structure and its modular design facilitates low-cost factory calibration. In addition, in some applications, the sensor can measure either strain or load.

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Significance

Many defense, industrial and commercial applications could (and some do) rely on very sensitive, rugged, reliable displacement sensors, to provide enhanced performance, overload protection, and/or health/safety monitoring. Some existing examples include the following:

- Monitoring strain in continuous sections and displacement across joints and air gaps in aircraft, bridges, dams, tunnels, monuments, buildings, elevators, presses, machine tools, cranes, aerial platforms, agricultural machines and other machinery
- Weighing vessels, silos, storage tanks and other load sensing applications

For bearings, displacement sensors are important alternatives to strain sensors when it comes to measuring load for enhanced performance and process control, overload protection, and health monitoring. For some bearing applications, displacement sensors are the only reasonable way to measure load. Unfortunately, the displacement sensors available today are too expensive for many applications and some require improvements in their performance and reliability.

The combination of higher reliability, greater accuracy, enhanced discrimination against the effects of undesired displacements and rotations, temperature information, rapid attachment/detachment, and the ability to bridge structural gaps/joints at a significantly lower cost are the main advantages of the developed MEMS displacement sensor over other comparable designs for many applications. It can also measure strain along continuous sections in an application structure and can function as a load cell.

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Accomplishments

Through the course of arriving at a sensor design that meets the above project objectives, six generations of displacement sensors were developed whose main characteristics are described in Table DS-1. The major differences in their construction can be summarized as follows:

1. Sensors GEN-1 thru GEN-4 use metal-foil strain elements while sensors GEN-5 and GEN-6 use MEMS strain elements.
2. Sensors GEN-1 thru GEN-5 incorporate separate strain and temperature sensing elements in their assembly. Sensor GEN-6 uses a MEMS module that integrates the strain and temperature sensing functions into one element.
3. Sensors GEN-1 thru GEN-3 have different substrate designs. Sensors GEN-4 thru GEN-6 use the same substrate design.
4. Sensors GEN-1 thru GEN-5 bond their strain element to the sensor substrate with adhesive, while sensor GEN-6 bonds its strain element with solder.

The first-generation (GEN-1) displacement sensor (Figure DS1) was developed with the finite-element analysis (FEA) guidance of several sensor substrate designs. It consists of a specially designed substrate (AS1symHp) with two-mounted holes at its elongated ends and a pedestal that is attached at its center and upon which a metal-foil strain gauge is bonded. A metal-foil strain gauge was used since at the time of construction the MEMS strain-sensor module was not fully developed. The displacement sensor attaches to the application structure with bolts, adhesives, welding, or any combination of the three and operates as a displacement sensor (i.e., extensometer), strain sensor, and/or load sensor. As a displacement sensor, it measures the relative displacement in the direction of its two contact pads having a gauge-length equal to the distance between the two inside edges of its contact-pads. Therefore, the measured displacement divided by the sensor gauge-length provides a measure of the average strain in the direction along the sensor contact-pads, the x-axis by definition. The sensor also acts as a load cell when calibration of its output signal as a function of the applied force in the x-direction is established. Special slots in the sensor substrate provide strong coupling of applied displacements, strains, and loads in the x-direction, while minimizing the cross coupling due to displacements in the y and z-direction, and to rotations about the x, y and z-axes. The sensor full strain range was measured at $\pm 550 \mu\epsilon$ and its sensitivity at $22 \mu\epsilon / \mu\text{m}$. The worst-case total error for displacements in the x-direction was $\leq \pm 0.40\%$ FDR-X. In addition, FEA predicted sensor reaction force of 60 N at the Full Displacement Range (FDR) of $\pm 25 \mu\text{m}$.

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The second-generation (GEN-2) displacement sensor (Figure DS2) was developed to produce a displacement sensor in a much smaller package than the first generation and with improved performance characteristics. It incorporates a unibody substrate (DS-4C) where the sensor pedestal and much-simplified substrate are combined into one piece and therefore it reduces manufacturing cost and enhances the sensor ruggedness and reliability. As in the case of the first generation, a metal-foil strain gauge was bonded on the pedestal with adhesive since at the time of construction the MEMS strain-sensor module was not fully developed. Conducted sensor tests at room temperature indicated large linear response to displacements applied in the x-direction over the sensor FDR of $\pm 8 \mu\text{m}$, with small slipping and small cross coupling from displacements applied in the y and z-directions and rotations applied about the x, y and z-directions. The sensor full strain range was measured at $\pm 500 \mu\epsilon$ and its sensitivity at $63 \mu\epsilon / \mu\text{m}$. The worst-case total error for displacements in the x-direction was $\leq \pm 0.49\%$ FDR-X. In addition, FEA predicted sensor reaction force of 48 N at FDR, which is significantly smaller than the 60 N of the first-generation displacement sensor.

The third-generation (GEN-3) displacement sensor (Figure DS3) was developed to significantly reduce coupling errors. It incorporates a DS-4Cnb substrate design that has all of the advantages of design DS-4C, but it significantly reduces coupling errors due to undesired applied displacements (in the y and z-directions) and rotations (about the x, y and z-directions) as indicated in Table DS-1. As in the case of the first and second-generation displacement sensors, a metal-foil strain gauge was bonded on the pedestal with adhesive. Conducted sensor tests at room temperature indicated large linear response to displacements applied in the x-direction over the sensor FDR of $\pm 13.5 \mu\text{m}$, with small slipping and small cross coupling from displacements applied in the y and z-directions and rotations applied about the x, y and z-directions. The sensor full strain range was measured at $\pm 800 \mu\epsilon$ and its sensitivity at $59 \mu\epsilon / \mu\text{m}$. The worst-case total error for displacements in the x-direction was $\leq \pm 0.20\%$ FDR-X. In addition, the sensor reaction force as predicted by FEA was 68 N at FDR, which is significantly larger than the 48 N of the second-generation displacement sensor.

The fourth-generation (GEN-4) displacement sensor (Figure DS4) was developed to bring the sensor reaction force back to the second-generation level. It incorporates a DS-4Cnb-Thin substrate design that is thinner, lighter, and cuts the reaction force in half, making it easier to hold in place without slipping. As in the case of the first, second and third-generation displacement sensors, a metal-foil strain gauge was bonded on the pedestal with adhesive. Conducted sensor tests at room temperature indicated large linear response to displacements applied in the x-direction over the sensor FDR of $\pm 13 \mu\text{m}$, with small slipping and small cross coupling from displacements applied in the y and z-directions and rotations applied about the x, y and z-directions. The sensor full strain range was measured at $\pm 500 \mu\epsilon$ and its sensitivity at $38 \mu\epsilon / \mu\text{m}$. The worst-case total error for displacements in the x-direction was $\leq \pm 0.20\%$ FDR-X. In addition, the sensor reaction force as predicted by FEA was 45 N at FDR, which is similar to the level of second-generation displacement sensor.

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In the fifth-generation (GEN-5) displacement sensor (Figure DS5), the newly developed Version #1 MEMS strain-sensor module was incorporated together with a DS-4Cnb-Thin substrate. Since the design of Version #1 MEMS chip does not include a eutectic-bonding layer, the MEMS strain-sensor module was bonded on the sensor substrate with adhesive. The sensor full strain range was measured at $\pm 480 \mu\epsilon$ and its sensitivity at $37 \mu\epsilon / \mu\text{m}$. As in the case of the fourth-generation displacement sensor, conducted sensor tests at room temperature indicated large linear response to displacements applied in the x-direction over the sensor FDR of $\pm 13 \mu\text{m}$, with small slipping and small cross coupling from displacements applied in the y and z-directions and rotations applied about the x, y and z-directions. The worst-case total error for displacements in the x-direction was $\leq \pm 0.20\%$ FDR-X. The use of MEMS strain-sensor module set the sensor bandwidth from DC to 2 kHz in comparison to the displacement sensors with metal-foil strain gauges whose bandwidth was from DC to 10 Hz.

The sixth-generation (GEN-6) displacement sensor (Figure DS6) incorporates Version #4 MEMS strain-sensor module with the DS-4Cnb-Thin substrate. Since the design of Version #4 MEMS chip includes a eutectic-bonding layer, the MEMS strain-sensor module was bonded on the sensor substrate with solder. Version #4 MEMS chip includes also an RTD element and therefore the displacement sensor did not have the need for an additional temperature-sensing element. The sensor full strain range was measured at $\pm 850 \mu\epsilon$ and its sensitivity at $65 \mu\epsilon / \mu\text{m}$. As in the case of the fourth and fifth-generation displacement sensors, conducted sensor tests at room temperature indicated large linear response to displacements applied in the x-direction over the sensor FDR of $\pm 13 \mu\text{m}$, with small slipping and small cross coupling from displacements applied in the y and z-directions and rotations applied about the x, y and z-directions. The worst-case total error for displacements in the x-direction was $\leq \pm 0.20\%$ FDR-X. In addition, the sensor bandwidth was from DC to 2kHz.

The DS-4Cnb-Thin design is also amenable to lower-cost stamping and laser cutting of the stainless steel substrate as shown in Figure DS7 where both stamping and laser-cutting techniques were used to manufacture a sample of stainless steel substrates. Several methods and materials were also investigated for the encapsulation and protection of displacement sensors. The material sought had to be a good electrical insulator, flexible (but tough), able to withstand a large temperature range, and able to seal the sensors from chemicals, liquids, and gases. A 3-piece mold was developed to encapsulate several prototype displacement sensors with different materials such as RTV silicone, fluorosilicone, and epoxies. The RTV silicone and fluorosilicone encapsulations yielded the best performance. Conducted tests at room temperature showed that there was little difference between the responses of displacement sensors without encapsulation and those encapsulated with fluorosilicone or RTV silicone. Since RTV silicone and fluorosilicone are soft materials, a protective boot of a harder, more durable polymer (acetal) was added around the soft inner fill as shown in Figure DS8. Table DS-2 summarizes the main features of an encapsulated displacement sensor with a DS-4Cnb-Thin substrate.

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Special signal condition electronics were designed to support the developed displacement sensors with either MEMS strain-sensor modules or metal-foil strain gauges. Figure DS9 shows two versions of the developed signal conditioning boards and Figure DS10 displays their main performance characteristics.

As it is mentioned in the Calibration and Testing section of this report, a fully automated long-term performance test system (Figure DS11) was developed specifically for the evaluation of displacement sensors. The system is capable of applying static and dynamic displacements to bolt-on displacement sensors and can simultaneously evaluate the performance of up to six displacement sensors at temperatures from -55°C to 180°C over the entire life of the attached sensors.

Several bolt-on displacement sensors were evaluated by this system as follows:

1. Five DS-4Cnb-Thin stamped substrates lasted over 400 million cycles at room temperature under the full operating displacement range.
2. One encapsulated displacement sensor with DS-4Cnb-Thin EDM'd substrate and a metal-foil strain gauge adhesively bonded on it, lasted over 400 million cycles at room temperature under the full operating displacement range.
3. Six DS-4Cnb-Thin laser-cut substrates with MEMS strain-sensor modules solder-bonded on them lasted over 400 million cycles at room temperature under the full operating displacement range. During this test, two of the sensors were connected to their signal conditioning electronics in order to monitor their output signals. No significant change in their performance was observed.

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Conclusions:

Over the past five years, efforts were successful in developing a low-cost, very sensitive, rugged MEMS displacement sensor and associated electronics capable of measuring displacements in one direction across a gap or solid section in a structure for real-world applications (Figure DS12).

The features and performance characteristics of the developed prototype MEMS displacement sensor are summarized in Figure DS8 as follows:

1. Small package: 39 mm x 16 mm x 7 mm
(1.5 in x 0.6 in x 0.3 in)
2. Bolt-on design provides fast, easy installation & maintainability
3. Large nearly linear response to displacements & strains applied in the x-direction (long axis)
4. Full-range (x-direction) (adjustable by design):
 - $\pm 13.5 \mu\text{m}$ (Applied displacement)
 - $\pm 1040 \mu\epsilon$ (Applied strain)
5. Over-range limit (x-direction):
 - $\pm 27 \mu\text{m}$ (Applied displacement)
 - $\pm 2080 \mu\epsilon$ (Applied strain)
6. Total error $< \pm 1\%$ of FDR
7. Operating bandwidth: DC to 2000 Hz
8. Small reaction force: $|F_x| \leq 45 \text{ N}$ for Full Range
9. Operating temperature range:
 - -40 to 85°C (Option I)
 - -40 to 150°C (Option A)
 - -55 to 70°C (Option Aerospace)

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Technology Transfer

During the MFREB program duration, several progress reports and program presentations were presented to members of ARO and ARL as follows:

1. August 31, 2005 – Annual progress report
2. September 9, 2005 – Program presentation
3. September 30, 2005– Interim progress report
4. August 14, 2006 – Interim progress report
5. August 31, 2006 – Annual progress report
6. September 22, 2006 – Program presentation
7. March 15, 2007 – Interim progress report
8. August 31, 2007 – Annual progress report
9. June 30, 2008 – Program presentation
10. August 31, 2008 – Annual progress report
11. December 31, 2008 – Interim progress report
12. March 26, 2009 – Program presentation
13. April 30, 2009 – Interim progress report
14. August 31, 2009 – Annual progress report
15. July 30, 2010 – Final program presentation
16. July 30, 2010 – Final program report

A prototype Micro-Strain/Displacement Sensor made from metal-foil strain gauge was displayed on a Toolcat™ (Utility Work Machine) at the SAE Commercial Vehicle Engineering Congress and Exhibition from October 30 to November 1, 2007 in Rosemount, IL.

A prototype Micro-Strain/Displacement Sensor made from metal-foil strain gauge was displayed on a Toolcat™ (Utility Work Machine) at the SAE World Congress and Exhibition from April 14 to April 17, 2008 in Detroit, MI.

A prototype MEMS Micro-Strain/Displacement Sensor made from MEMS piezoresistive strain-sensor module was displayed on a force-sensing beam at the SAE World Congress and Exhibition from April 14 to April 17, 2008 in Detroit, MI.

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In January 2008, the potential application of MEMS strain sensors and displacement sensors to bridge usage and health monitoring was discussed with representatives of the Army's Engineering Research and Development Center (ERDC-GSL-MS and ERDC-GSL-MS).

In December 2008, a test was conducted to monitor the loads from traffic on a public bridge using several bolt-on displacement sensors made from MEMS piezoresistive strain-sensor modules. The conducted test included both wired and wireless hook-up configurations (using Timken's wireless StatusCheck[®] 2.4 system). An accompanying report was issued on April 30, 2009 describing details of the conducted test.

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MEMS Displacement Sensors

**Developed under the
MEMS for Rolling-Element
Bearings Program**

July 30, 2010

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Table DS-1: Main characteristics of developed displacement sensors

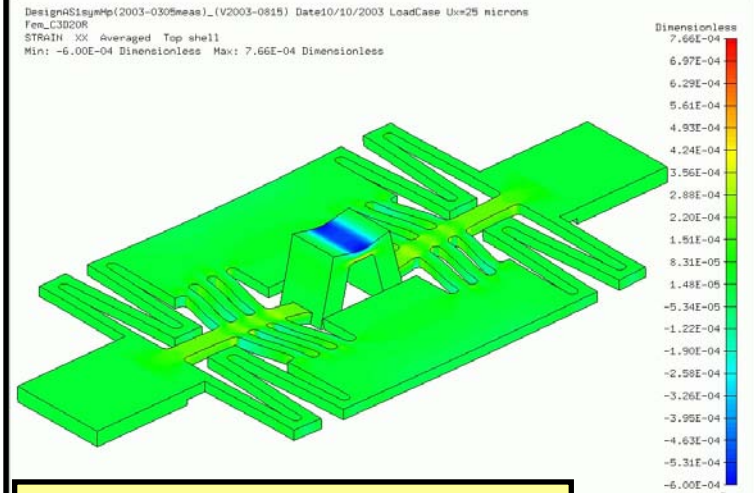
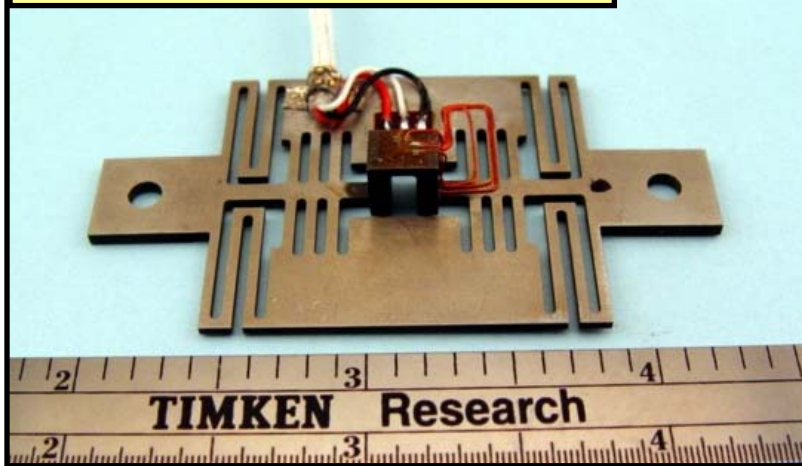
Parameter	DS_GEN-1	DS_GEN-2	DS_GEN-3	DS_GEN-4	DS_GEN-5	DS_GEN-6
Substrate	AS1symHp	DS-4C	DS-4Cnb	DS-4Cnb-Thin	DS-4Cnb-Thin	DS-4Cnb-Thin
Strain Gauge	Metal-Foil	Metal-Foil	Metal-Foil	Metal-Foil	MEMS w/o RTD	MEMS w/ RTD
Temperature Element	RTD	RTD	RTD	RTD	RDT	None
Strain Element Bond	Adhesive-Bond	Adhesive-Bond	Adhesive-Bond	Adhesive-Bond	Adhesive-Bond	Solder-Bond
Bandwidth	DC - 10 Hz	DC - 10 Hz	DC - 10 Hz	DC - 10 Hz	DC - 2 kHz	DC - 2 kHz
Full X-Displ. Range (FDR-X)	$\pm 25 \mu\text{m}$	$\pm 8 \mu\text{m}$	$\pm 13.5 \mu\text{m}$	$\pm 13 \mu\text{m}$	$\pm 13 \mu\text{m}$	$\pm 13 \mu\text{m}$
Full Strain Range	$\pm 550 \mu\epsilon$	$\pm 500 \mu\epsilon$	$\pm 800 \mu\epsilon$	$\pm 500 \mu\epsilon$	$\pm 480 \mu\epsilon$	$\pm 850 \mu\epsilon$
Sensitivity	$22 \mu\epsilon/\mu\text{m}$	$63 \mu\epsilon/\mu\text{m}$	$59 \mu\epsilon/\mu\text{m}$	$38 \mu\epsilon/\mu\text{m}$	$37 \mu\epsilon/\mu\text{m}$	$65 \mu\epsilon/\mu\text{m}$
X-Displ Error (3 σ Dev. From Linear Fit)	$\leq \pm 0.40 \%$ of FDR-X	$\leq \pm 0.49 \%$ of FDR-X	$\leq \pm 0.20 \%$ of FDR-X	$\leq \pm 0.20 \%$ of FDR-X	$\leq \pm 0.39 \%$ of FDR-X (*)	$\leq \pm 0.23 \%$ of FDR-X (**)
Y-Displ Cross Coupling Error	$\leq \pm 0.50 \%$ @ FDR-X/micron	$\leq \pm 0.40 \%$ @ FDR-X/micron	$\leq \pm 0.07 \%$ @ FDR-X/micron	$\leq \pm 0.07 \%$ @ FDR-X/micron	$\leq \pm 0.07 \%$ @ FDR-X/micron	$\leq \pm 0.07 \%$ @ FDR-X/micron
Z-Displ Cross Coupling Error	$\leq \pm 0.40 \%$ @ FDR-X/micron	$\leq \pm 0.50 \%$ @ FDR-X/micron	$\leq \pm 0.04 \%$ @ FDR-X/micron	$\leq \pm 0.04 \%$ @ FDR-X/micron	$\leq \pm 0.04 \%$ @ FDR-X/micron	$\leq \pm 0.04 \%$ @ FDR-X/micron
X-Rot Cross Coupling Error	$\leq \pm 0.50 \%$ @ FDR-X/0.1 milliradian	$\leq \pm 0.36 \%$ @ FDR-X/0.1 milliradian	$\leq \pm 0.18 \%$ @ FDR-X/0.1 milliradian	$\leq \pm 0.18 \%$ @ FDR-X/0.1 milliradian	$\leq \pm 0.18 \%$ @ FDR-X/0.1 milliradian	$\leq \pm 0.18 \%$ @ FDR-X/0.1 milliradian
Y-Rot Cross Coupling Error	$\leq \pm 0.50 \%$ @ FDR-X/0.1 milliradian	$\leq \pm 0.26 \%$ @ FDR-X/0.1 milliradian	$\leq \pm 0.04 \%$ @ FDR-X/0.1 milliradian	$\leq \pm 0.04 \%$ @ FDR-X/0.1 milliradian	$\leq \pm 0.04 \%$ @ FDR-X/0.1 milliradian	$\leq \pm 0.04 \%$ @ FDR-X/0.1 milliradian
Z-Rot Cross Coupling Error	$\leq \pm 0.60 \%$ @ FDR-X/0.1 milliradian	$\leq \pm 0.32 \%$ @ FDR-X/0.1 milliradian	$\leq \pm 0.22 \%$ @ FDR-X/0.1 milliradian	$\leq \pm 0.22 \%$ @ FDR-X/0.1 milliradian	$\leq \pm 0.22 \%$ @ FDR-X/0.1 milliradian	$\leq \pm 0.22 \%$ @ FDR-X/0.1 milliradian
Reaction Force @ FDR-X	60 N	48 N	68 N	45 N	45 N	45 N
Notes:					(*): Quadratic Fit	(**): Cubit Fit

Table DS-2: Main features of an encapsulated sensor w / DS-4Cnb-Thin substrate

- 1. Bolt-on design provides fast, easy installation & maintainability**
- 2. Large nearly linear response to displacements & strains applied in the X-direction (long axis)**
- 3. Full range (X-direction) (adjustable by design):**
 - $\pm 13.5 \mu\text{m}$ (Applied Displacement)
 - $\pm 1040 \mu\epsilon$ (Applied Strain)
- 4. Over-range limit (X-direction):**
 - $\pm 27 \mu\text{m}$ (Applied Displacement)
 - $\pm 2080 \mu\epsilon$ (Applied Strain)
- 5. Total error $< \pm 1\%$ of FDR**
- 6. Operating bandwidth: DC to 2000 Hz**
- 7. Small reaction force: $|F_x| \leq 45 \text{ N}$ for Full Range**
- 8. Operating temperature range:**
 - -40 to 85°C (Option I)
 - -40 to 150°C (Option A)
 - -55 to 70°C (Option Aerospace)
- 9. Small package: 39 mm x 16 mm x 7 mm
(1.5 in x 0.6 in x 0.3 in)**

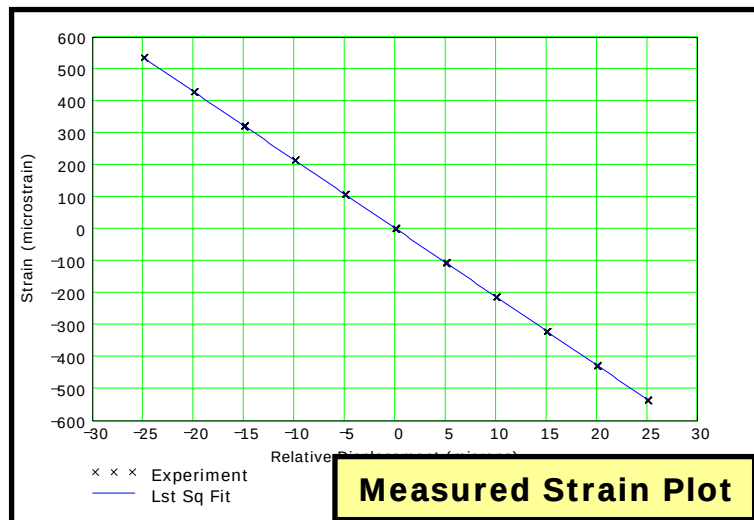
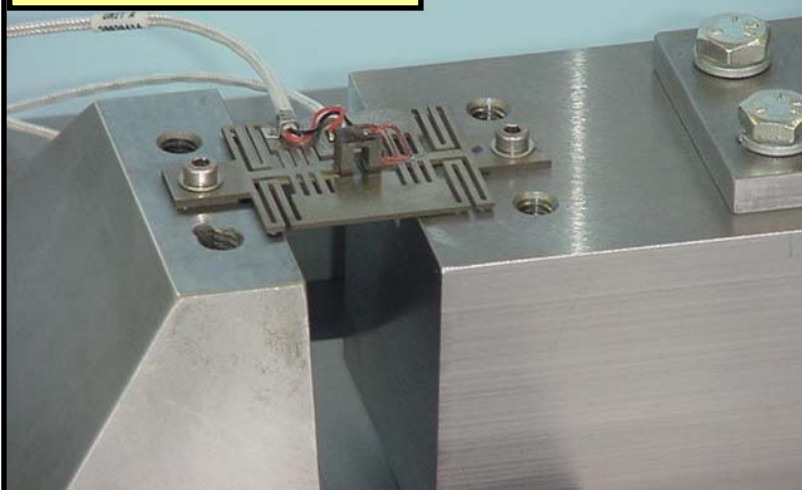
Figure DS1: GEN-1 displacement sensor w/ metal-foil strain gauge

Sensor Substrate w/ MF Gauge



AS1symHp Substrate Design

Sensor Across a Gap



Measured Strain Plot

Figure DS2: GEN-2 displacement sensor w/ metal-foil strain gauge

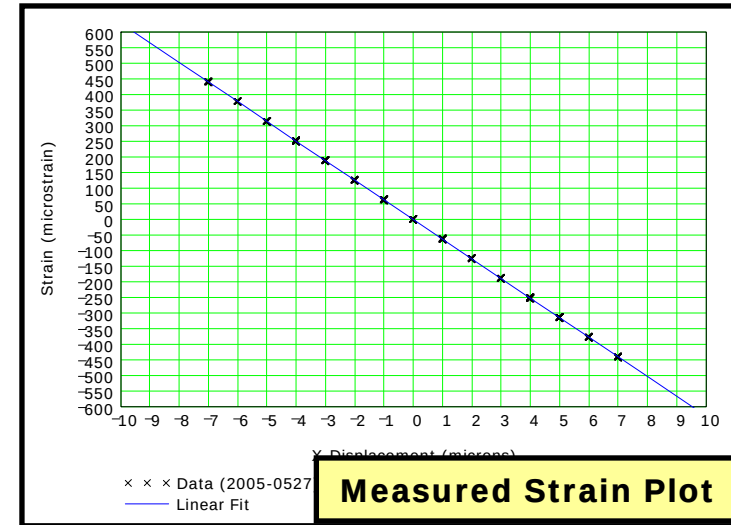
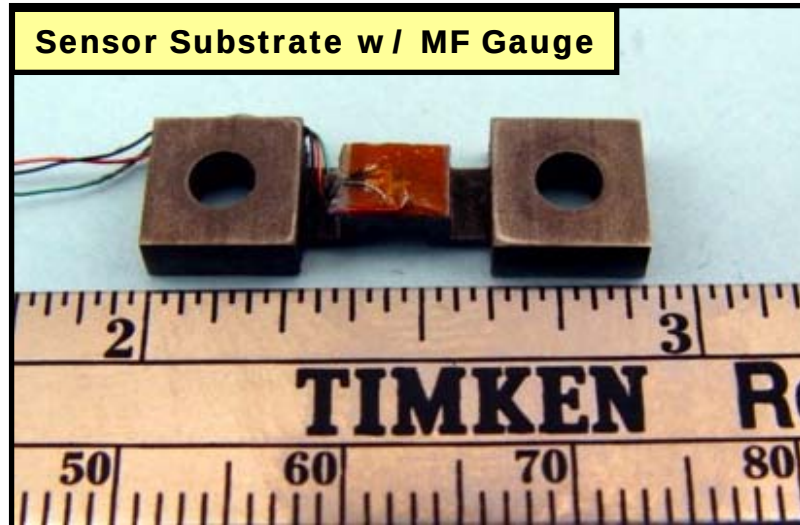
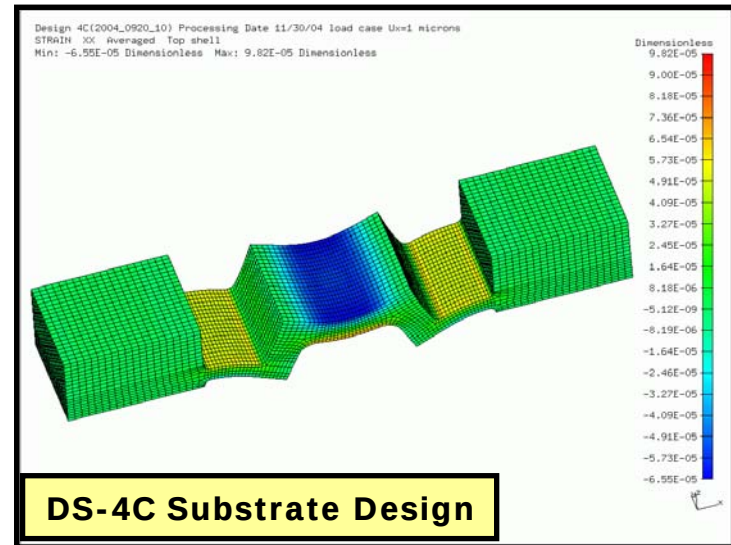


Figure DS3: GEN-3 displacement sensor w/ metal-foil strain gauge

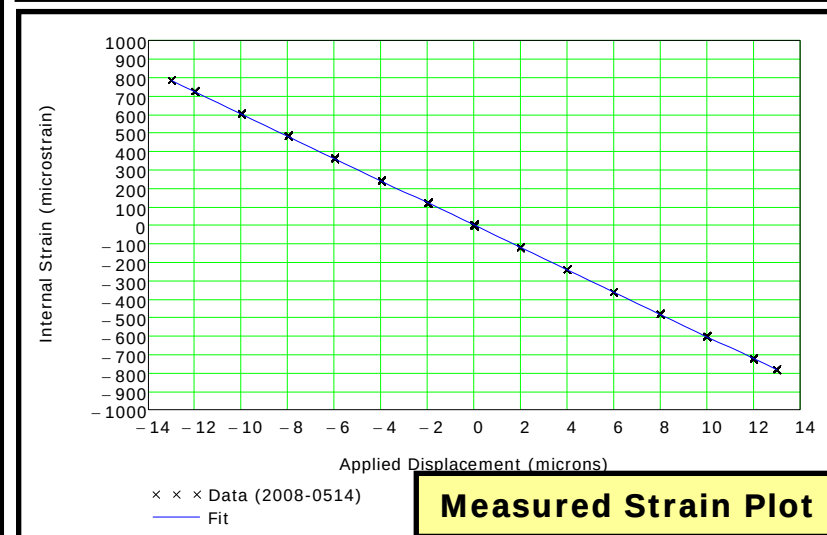
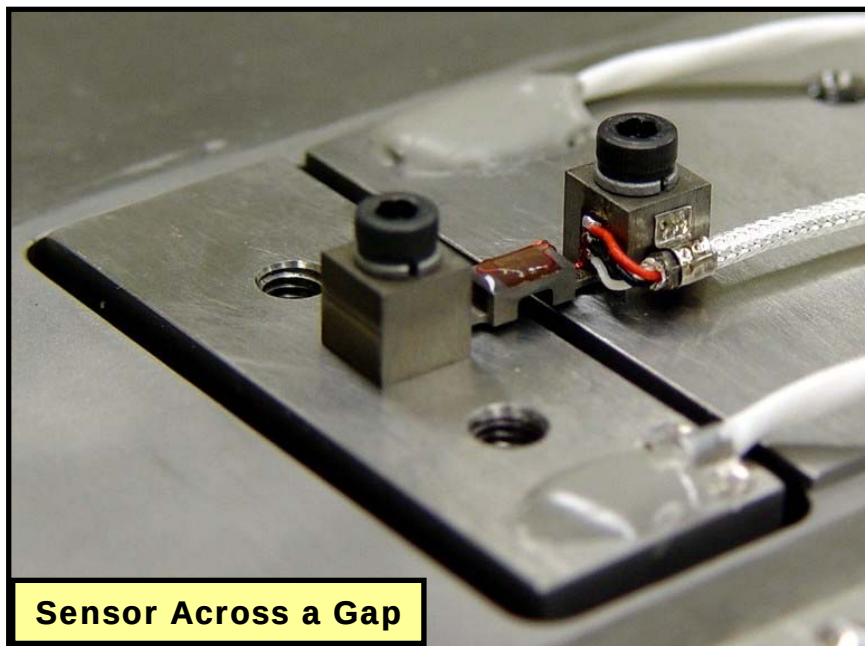
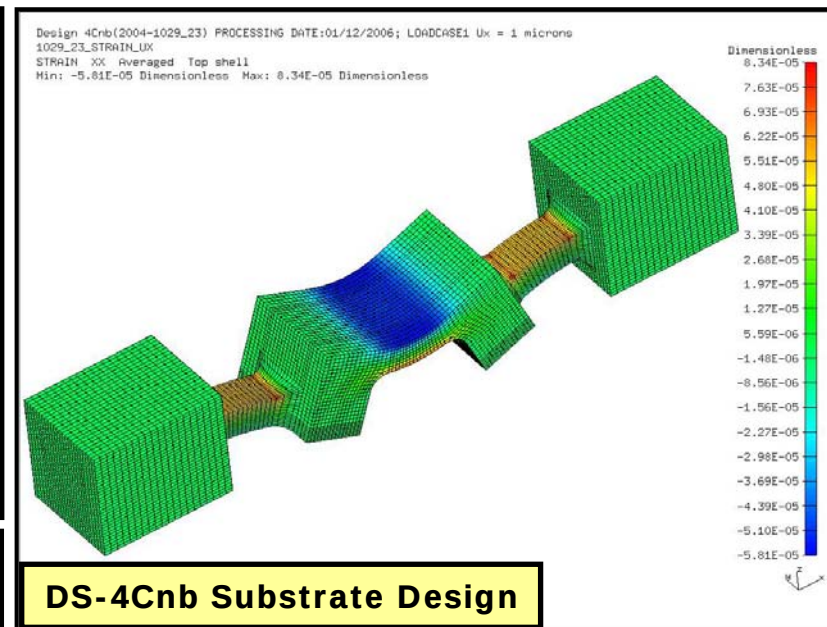
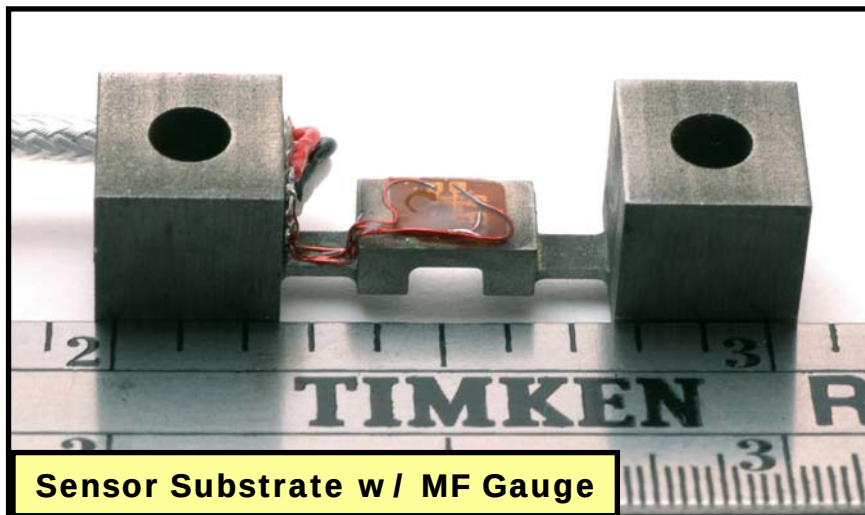


Figure DS4: GEN-4 displacement sensor w/ metal-foil strain gauge

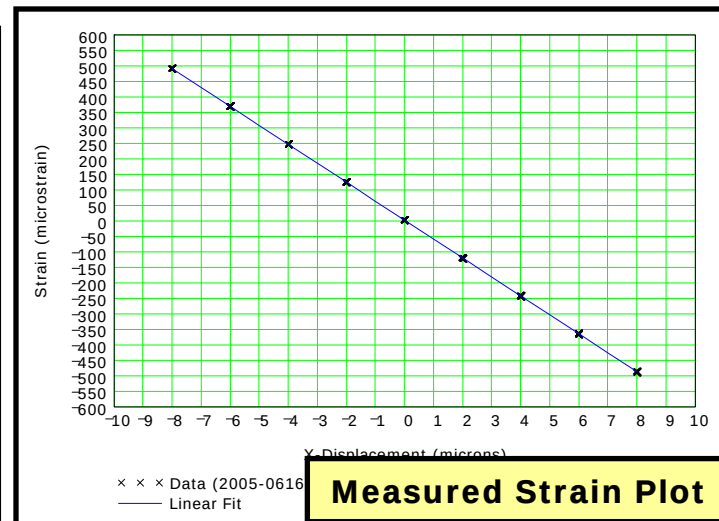
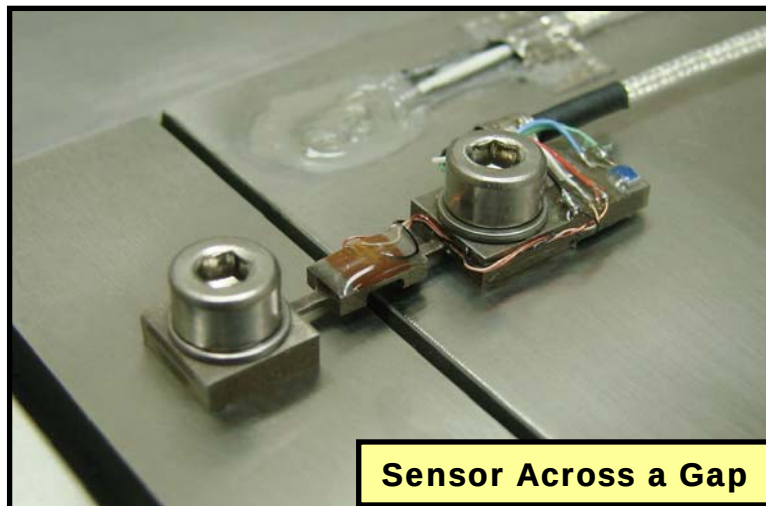
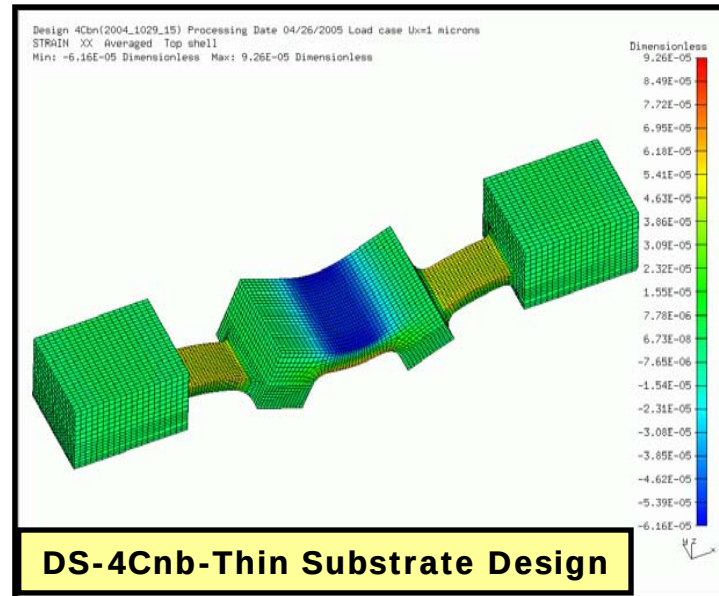
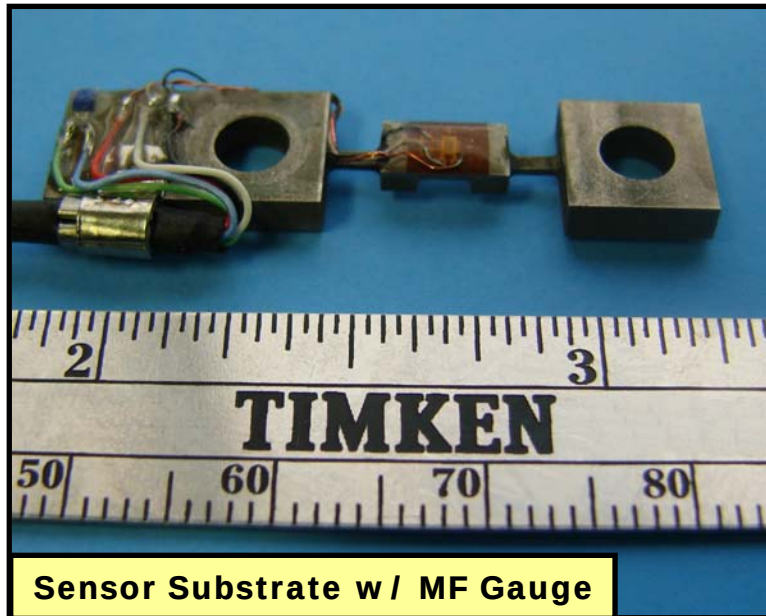
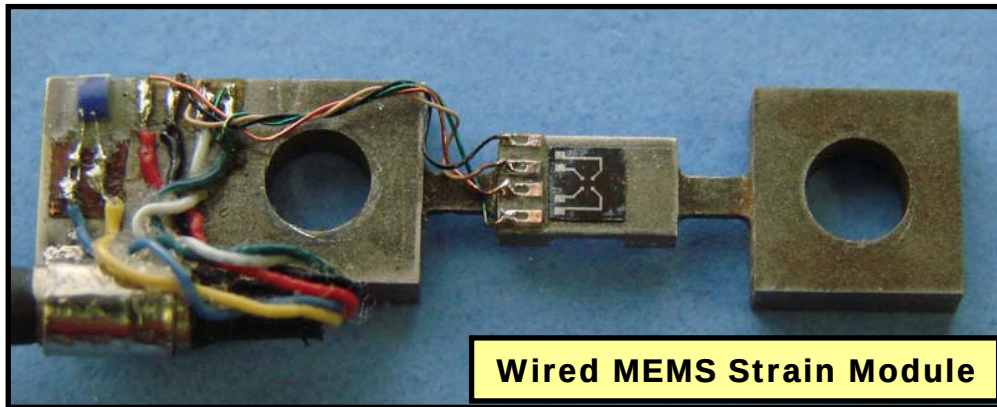
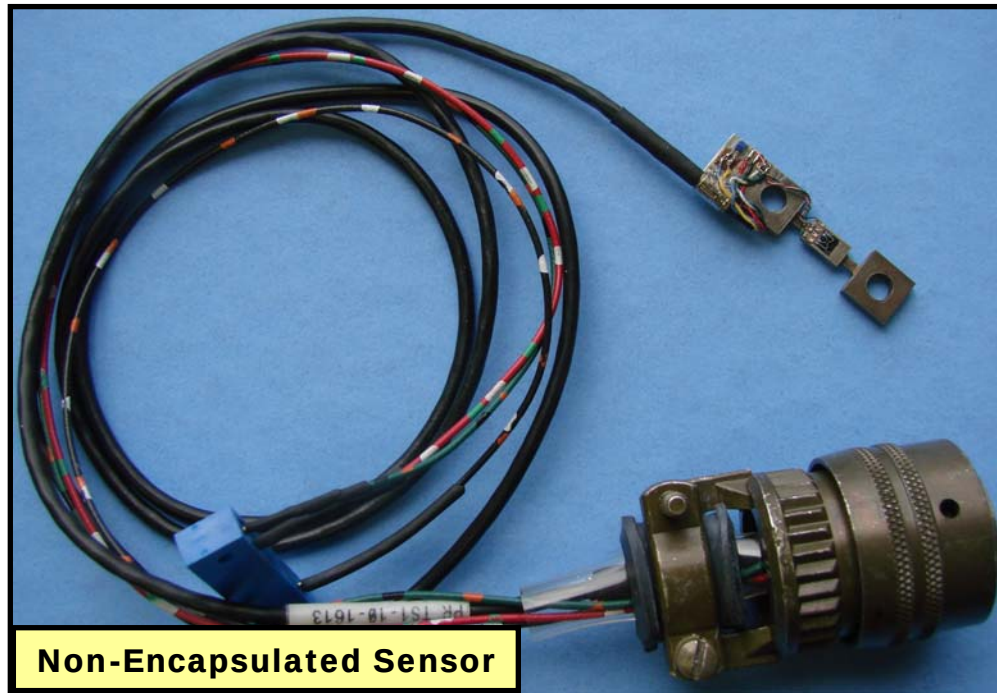


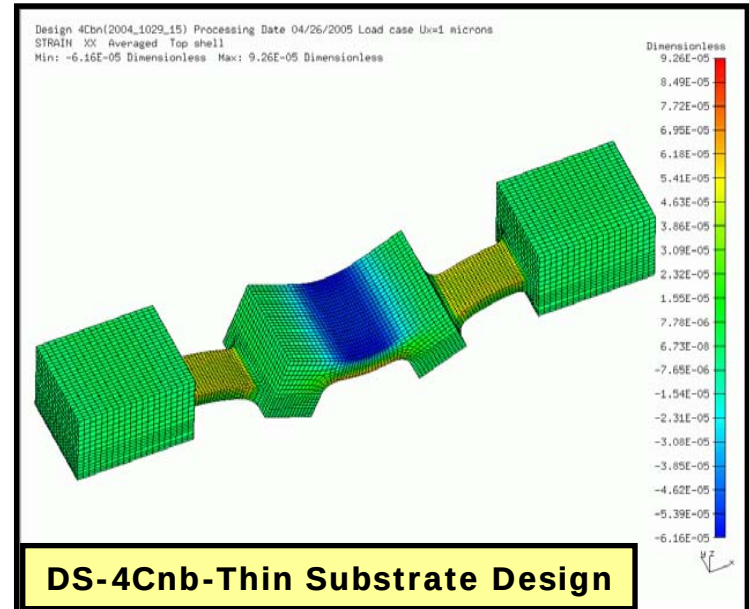
Figure DS5: GEN-5 displacement sensor w/ MEMS strain module (w/o RTD)



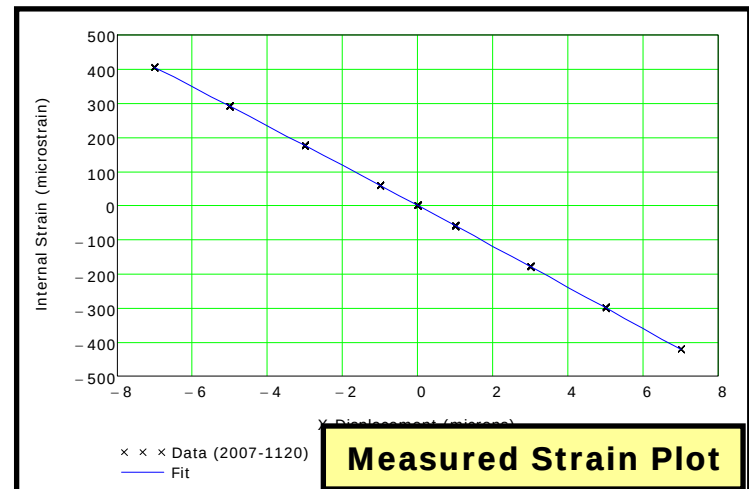
Wired MEMS Strain Module



Non-Encapsulated Sensor



DS-4Cnb-Thin Substrate Design



Measured Strain Plot

Figure DS6: GEN-6 displacement sensor w/ MEMS strain module (w/ RTD)

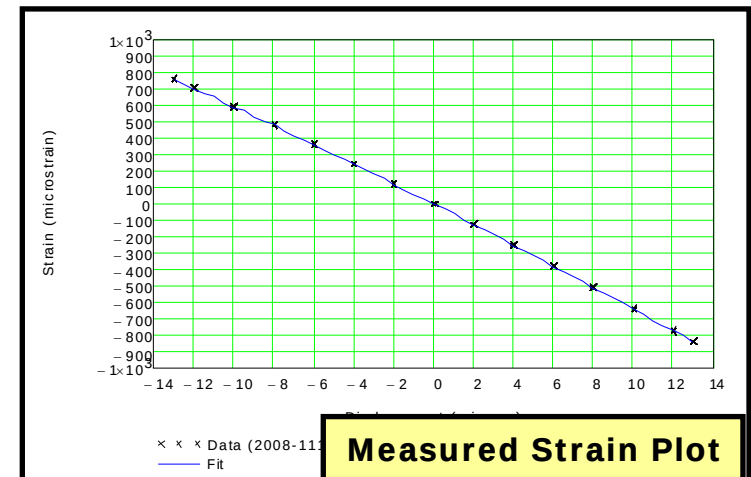
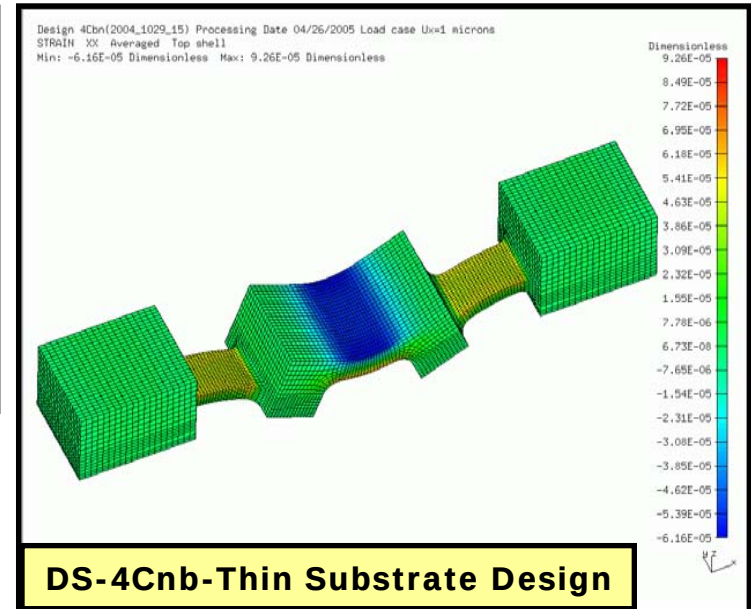
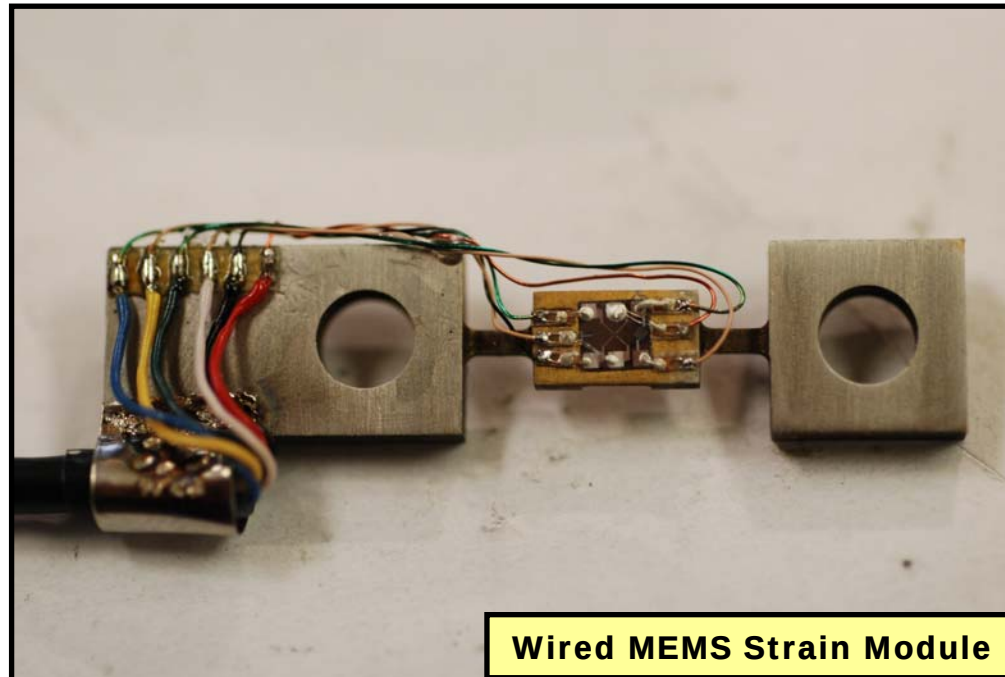
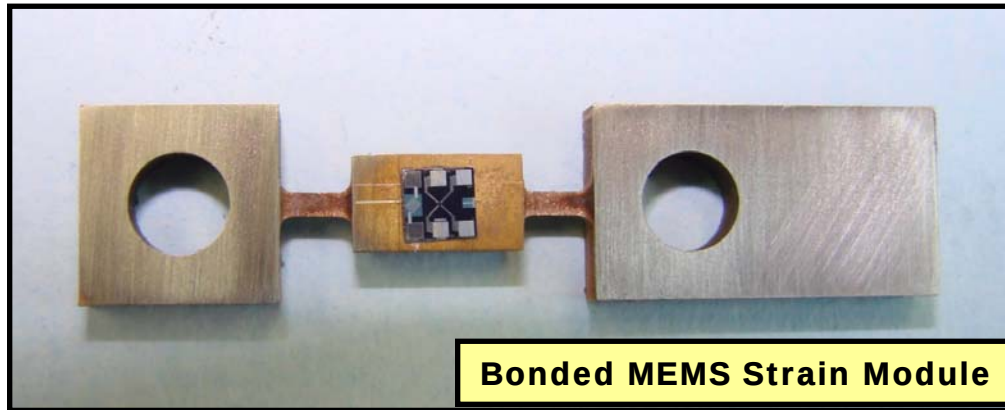
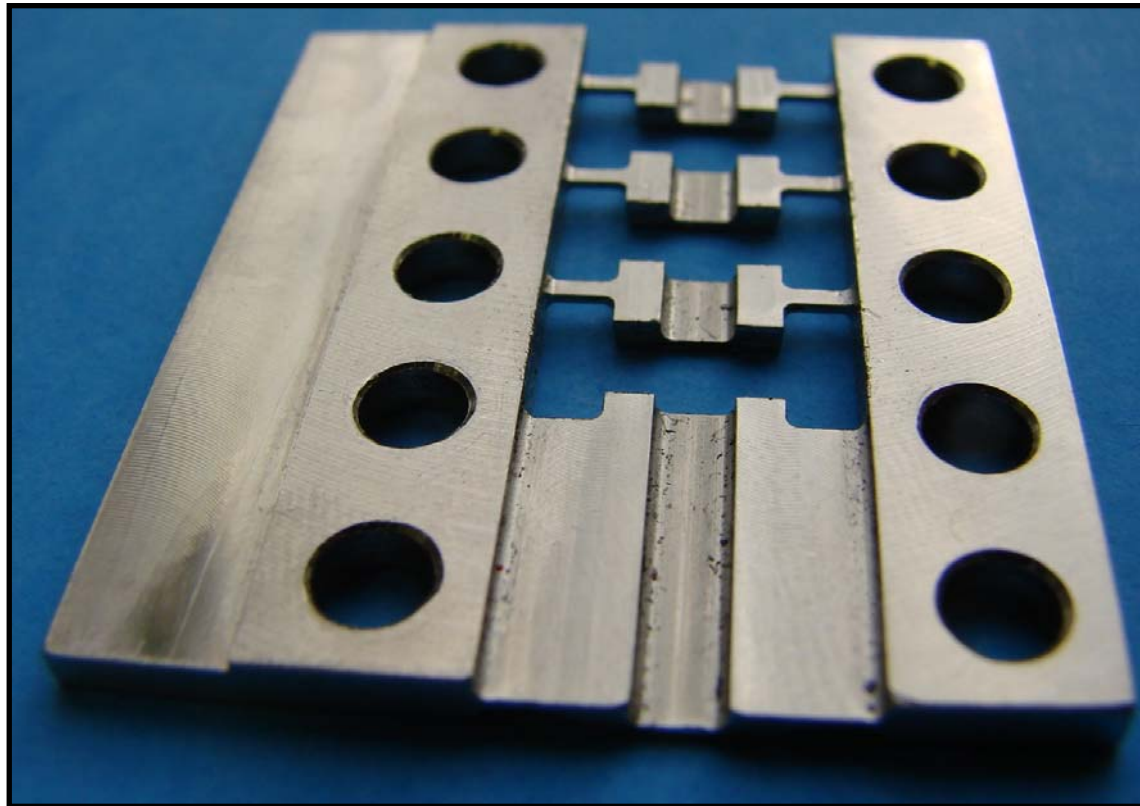
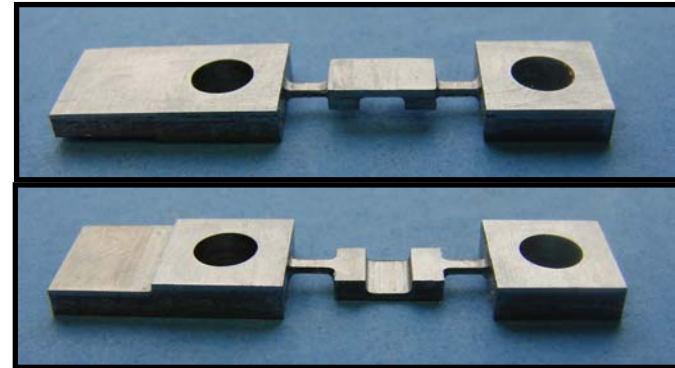


Figure DS7: DS-4Cnb-Thin substrate fabrication



**DS-4Cnb-Thin
Substrate Fabrication**

**Substrates w/
Stamped Inner Portion**



**Substrates w/ Laser-Cut
Inner Portion & Bolt Holes**

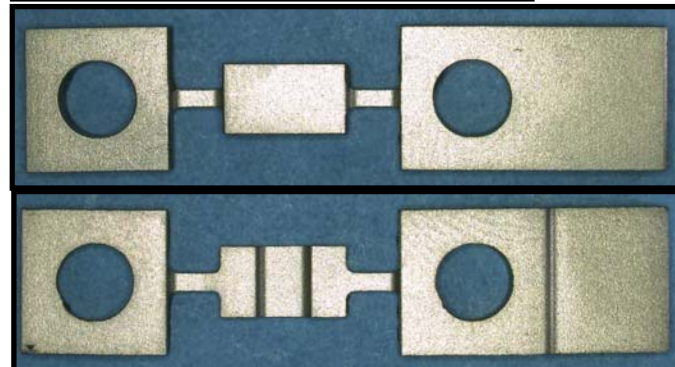
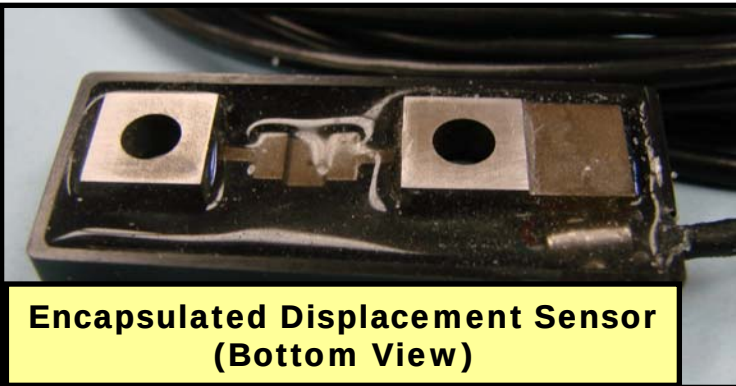


Figure DS8: Encapsulated sensor w / DS-4Cnb-Thin substrate

**Encapsulated Displacement Sensor
(Top View)**



**Encapsulated Displacement Sensor
(Bottom View)**



**Encapsulated Sensor
w / Attached Cable
& Connector**

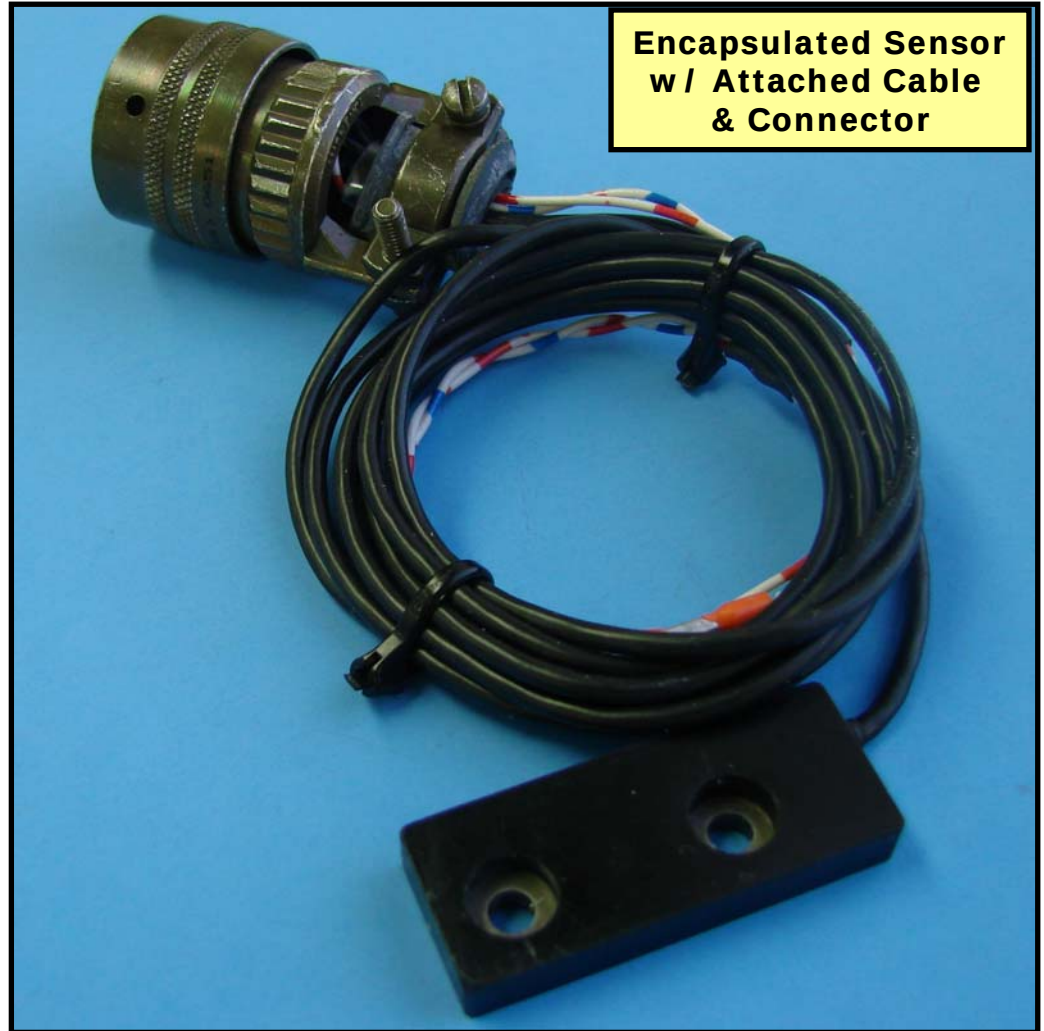
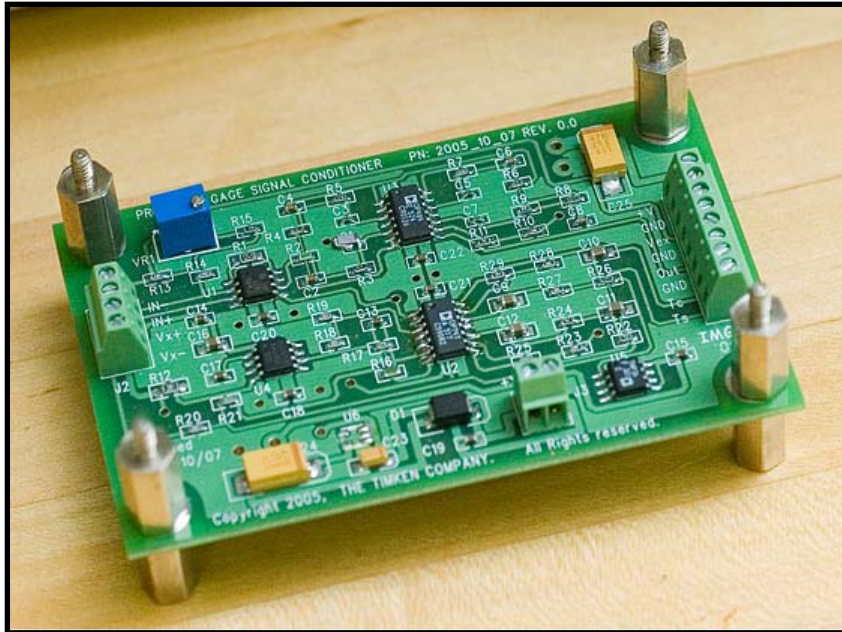
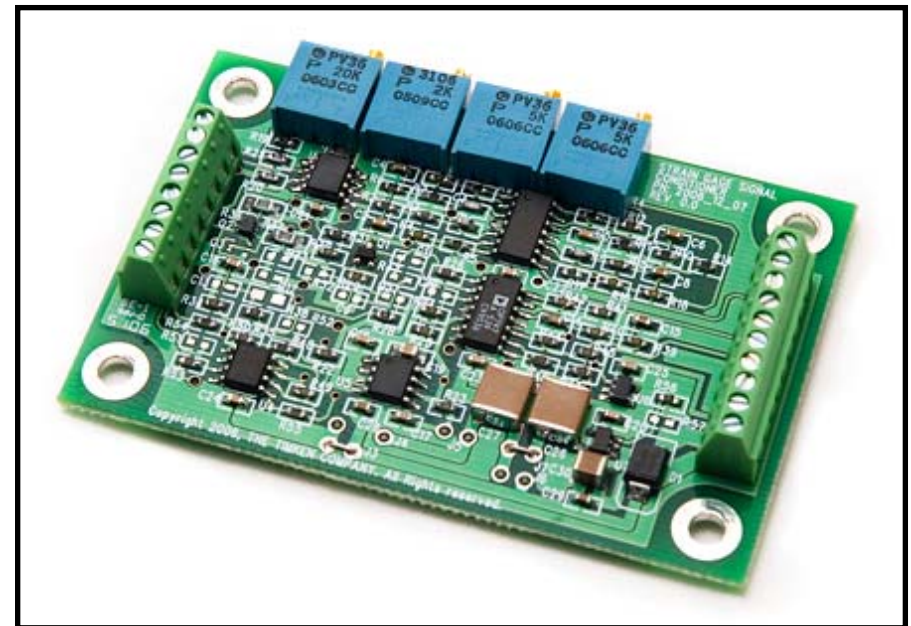


Figure DS9: Developed signal conditioning boards



Signal Conditioning Board – Version 1

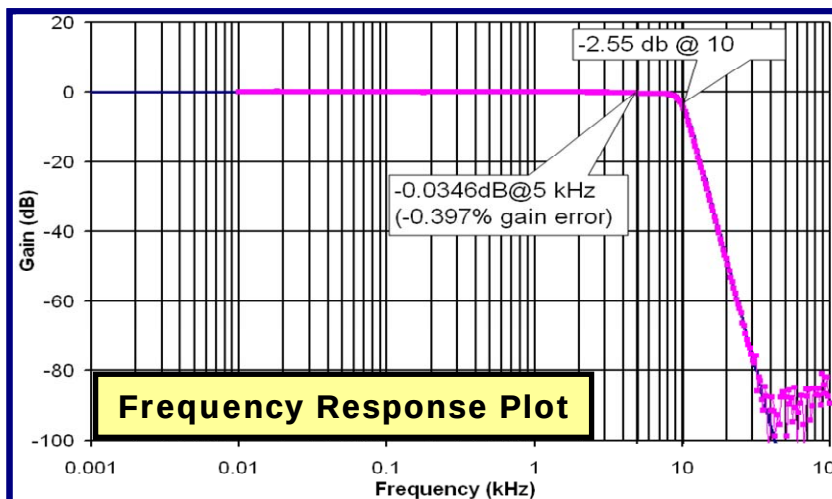


Signal Conditioning Board – Version 2

Figure DS10: Performance characteristics of signal conditioning electronics

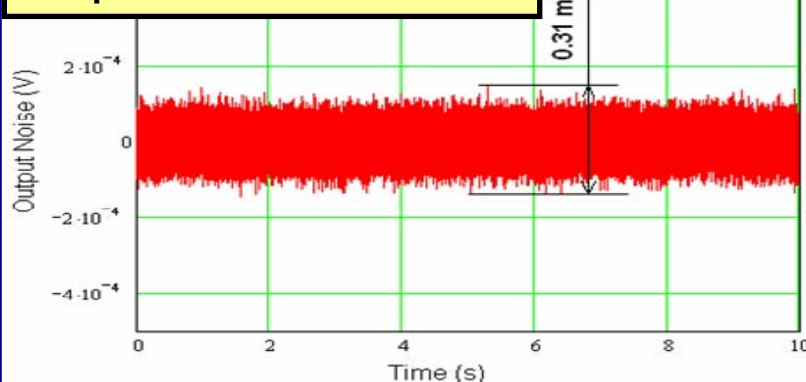
Main Features of Signal-Conditioning Board

1. Supports MEMS piezoresistive and metal-foil strain gages
2. Temperature sensing capability
3. Output noise
 - $\pm 0.155\text{mV(peak)}$
{equivalent to $\pm 0.075 \mu\epsilon(\text{peak})$ }
4. Frequency response (gain)
 - -0.0346 dB at 5 kHz; -2.55 dB at 10 kHz
 (GOAL: $\pm 0.087\text{dB}$ at 5 kHz; $\pm 3 \text{ dB}$ at 10 kHz)

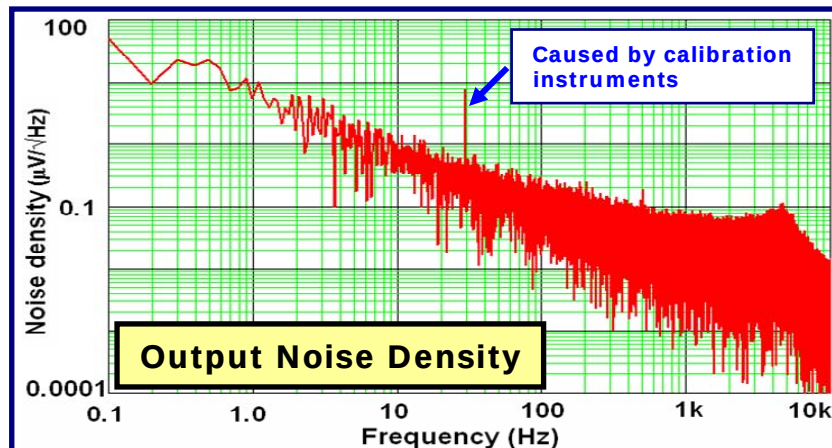


Frequency response (gain)
(-0.0346 dB at 5 kHz; -2.55 dB at 10 kHz)

Output Noise Measurement



Output noise (for 10 seconds period)
0.31 mV peak-to-peak {equivalent to $\pm 0.075 \mu\epsilon(\text{peak})$ }



Output noise density
(sampling rate 50 kHz)

Figure DS11: Displacement sensor long-term performance test system

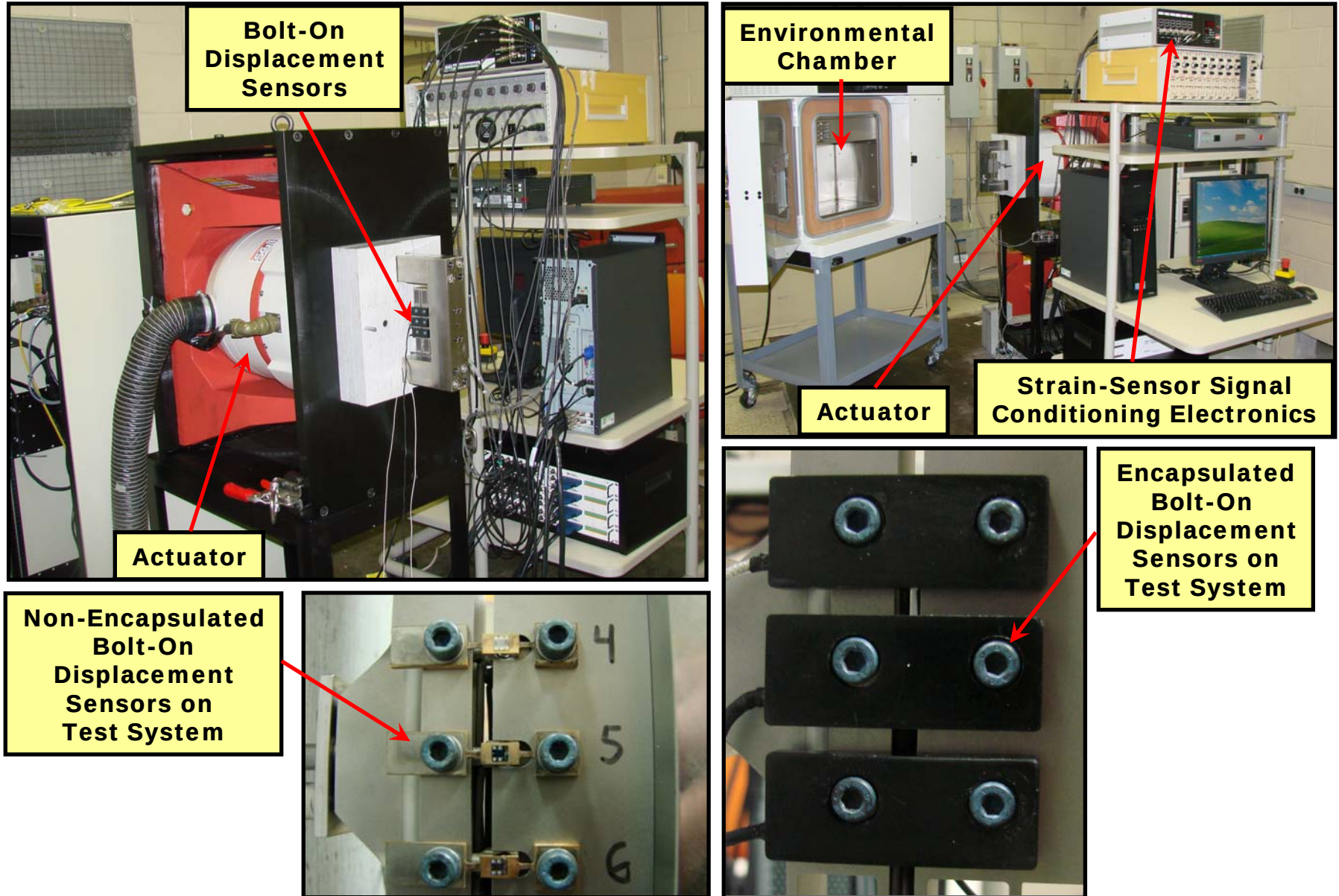
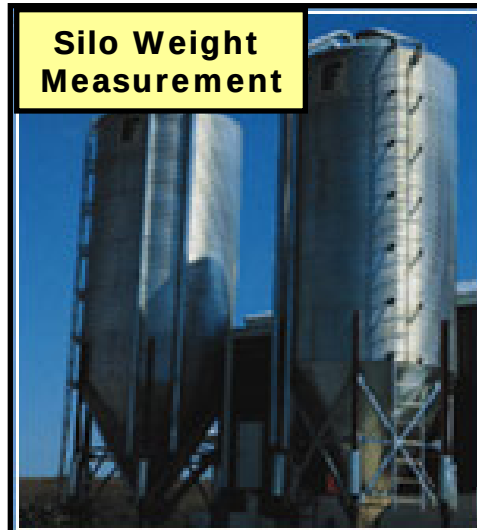


Figure DS12: GEN-4 displacement sensors – Potential applications



Final Report - March 1, 2005 through April 30, 2010
MEMS for Rolling-Element Bearings Program (Proposal Number 48371-EG)

Program: MEMS for Rolling-Element Bearings
Project: Calibration and Testing for the MEMS Strain Sensor Modules
R&D by: The Timken Company

Objectives

The primary objective of this project was to develop means of evaluating the performance of MEMS strain and displacement sensors and through these means to evaluate the performance of developed MEMS strain and displacement sensors.

Approach

Measurement of MEMS strain sensor's response to static and dynamic longitudinal (S_x), lateral (S_y), and shear (S_{xy}) surface strains in compression and tension was required. Available standard four-point bending test rigs (ASTM Standard E855-90) measured strain sensor responses to only static applied strains and had many limitations. They required strain sensors permanently bonded to a long narrow bar actuated in a bending mode to produce a uniform strain along its long axis (x-direction) in either compression or tension, depending on its orientation. Making strain measurements on each sensor in compression and tension was cumbersome and if the strain sensors were permanently bonded, one can only measure the component of strain along the axis of the bar. However, there was a need to measure each sensor's response to strains applied parallel to the axis of the bar, strains applied perpendicular to the axis of the bar, and to in-plane shear strains. Instruments with these combined measurement capabilities did not exist. Additionally, the accuracy that standard systems were capable of achieving, did not meet the needed requirements. Therefore, this problem was confronted by developing several calibration/test systems, which could be used in combination to achieve the desired results.

A set of additional calibration/test systems were also developed such as the long-term performance test system, the vibration test system, the displacement test system, and the creep test system in order to further evaluate the performance of MEMS strain and displacement sensors under various other applied conditions.

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Significance

To aid the development of new MEMS strain and displacement sensors, calibration/test systems were needed to be developed in order to evaluate the sensor performance and to calibrate the sensor output signal response. This requires development of very sensitive test systems with small errors to have the capability of evaluating the developed sensor output characteristics with high precision. Additionally, these sensors required dynamic evaluation, over their life, and throughout their operating temperature range. This was not a trivial task as the targeted performances of these new MEMS sensors were superior to the performance of conventional sensor devices.

Accomplishments

The first developed test system was an enhanced 4-point bending calibration/test unit (Figure CT1). The system measures the response of each strain sensor bonded to a stainless-steel test beam to statically applied single-components of strain (S_x or S_y). A four-point bending test beam is also shown in Figure CT1 with two MEMS piezoresistive strain-sensor modules solder-bonded to it prior to their cable attachment. Initially the developed system demonstrated repeatability to within $\pm 0.5 \mu\epsilon$ to $\pm 1 \mu\epsilon$ of applied strains, which was 4 to 8-times better than other known units. Later on, a computer-controlled actuator and additional features to the control and data acquisition program were added to enhance the overall system performance. The system is now fully automated and is able to apply compressive and tensile strains with a manual change of the instrumented beam. System repeatability for strain measurements has been improved to within $\pm 0.02\%$ to $\pm 0.04\%$ of full scale, which is 10 to 20 times better than other known systems.

The second developed test system was a shear strain calibration/test unit designed to measure the response of each strain sensor bonded to a stainless-steel test beam to static in-plane shear strains (S_{xy}) in compression and in tension (Figure CT2). The system uses the same instrumented test beam as the one in the 4-point bending calibration/test unit. Therefore, by using both systems, each strain sensor on a given beam can be tested for applied (S_x and S_{xy}) or (S_y and S_{xy}), depending on orientation. The FEA modeling of the stainless-steel test beam is also shown in Figure CT2 where the uniform-strain area colored in red denotes the area the strain sensors are being bonded. Initially, the system was evaluated with metal-foil strain sensors mounted on a 2.5 mm thick beam to measure the in-plane shear strain induced by applying a torsion load along the long axis of the beam. Repeatability was demonstrated to within $\pm 0.1\%$ of full scale of applied strains when the sensors were tested in a purely tensile or compressive mode. It was also repeatable to within $\pm 0.1\%$ of full scale of the applied strains when the system was operated from a negative strain, through a zero point unloading the beam, and then to a positive strain.

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Although a small hysteresis was present, the shear calibration system exhibited a linear response of the strain sensor to the applied torques and angular displacement of the beam. To enable the shear strain calibration/test unit to automatically apply and maintain higher torsion loads and to enhance the overall system performance, a motorized rotary stage was added to the system and additional features were implemented to its control and data acquisition program. The new hardware/software configuration has increased the system torsion load capacity of the unit from ± 20 Nm to ± 30 Nm and has reduced the overall test time and effort.

The third developed test system was based on a uniform-strain beam concept as shown in Figure CT3 and ASTM Standard E251-92 that is capable of applying static and dynamic strains (S_x or S_y) to sensors. Its design features high-precision actuation, load sensing, and a high-resolution optical laser displacement sensor for strain correlation. The system is able to apply compressive and tensile strains on the beam without any manual change in configuration. Many FEA simulations were conducted to investigate the possible effects on the uniform strain region intrinsic to the beam design. With the latest implemented beam design, a 55 mm long uniform-strain region with a uniformity of 0.1% can be achieved on the beam surface where the strain sensors are being bonded as shown in Figure CT3. The system has exhibited repeatability to within $\pm 0.6 \mu\epsilon$ of the applied strains and its small size facilitates testing over the entire strain-sensor operating temperature range.

In order to test the output signal stability of bonded strain sensors, a fourth test system was developed that consists of a creep test stand, a computer controlled data acquisition system, and a manual loading/unloading mechanism as shown in Figure CT4. The creep test stand incorporates the same uniform-strain beam design as in the third test system with the bonded strain sensors wired to signal condition electronics. Its small size allows it also to be placed inside an environmental chamber where the bonded strain sensors can be tested over the temperature range of -55°C to 180°C .

Three additional calibration/test systems were developed specifically for the evaluation of displacement sensors. The first system (Figure CT5) incorporates a computer-controlled micro-positioning unit capable of applying automatically static and dynamic displacements to the attached sensors in the x, y, and z-direction (in any combination), and static and dynamic rotations to sensors about the x, y, and z-directions (in any combination). Its data acquisition system can support several reference temperature sensors attached to the micro-positioning unit. The second system (Figure CT6) is an automated vibration test system that determines the frequency response of the attached displacement sensor to vibrations applied in the y or z-direction of the sensor over the frequency band of 2 to 6,500 Hz dependent upon how the sensor is mounted on the test stand. Finally the third system (Figure CT7) is a fully automated long-term performance test system capable of applying static and dynamic displacements to bolt-on displacement sensors and can simultaneously evaluate the performance of up to six displacement sensors at temperatures from -55°C to 180°C over the entire life of the attached sensors.

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Conclusions:

The above project efforts led to the development of seven very sensitive test systems with small errors that have the capability of evaluating the performance and output characteristics of developed MEMS strain and displacement sensors with high precision.

Technology Transfer

During the MFREB program duration, the following progress reports and program presentations were presented to members of ARO and ARL where calibration & testing of MEMS strain sensors played a key roll:

1. August 31, 2005 – Annual progress report
2. September 9, 2005 – Program presentation
3. September 30, 2005– Interim progress report
4. August 14, 2006 – Interim progress report
5. August 31, 2006 – Annual progress report
6. September 22, 2006 – Program presentation
7. March 15, 2007 – Interim progress report
8. August 31, 2007 – Annual progress report
9. June 30, 2008 – Program presentation
10. August 31, 2008 – Annual progress report
11. December 31, 2008 – Interim progress report
12. March 26, 2009 – Program presentation
13. April 30, 2009 – Interim progress report
14. August 31, 2009 – Annual progress report
15. July 30, 2010 – Final program presentation
16. July 30, 2010 – Final program report

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During the MFREB program duration, the following MEMS technology demonstration and implementation activities were also conducted where calibration & testing of MEMS strain sensors supported the development of implemented devices:

1. A prototype Micro-Strain/Displacement Sensor made from metal-foil strain gauge was displayed on a Toolcat™ (Utility Work Machine) at the SAE Commercial Vehicle Engineering Congress and Exhibition from October 30 to November 1, 2007 in Rosemount, IL.
2. A prototype Micro-Strain/Displacement Sensor made from metal-foil strain gauge was displayed on a Toolcat™ (Utility Work Machine) at the SAE World Congress and Exhibition from April 14 to April 17, 2008 in Detroit, MI.
3. A prototype MEMS Micro-Strain/Displacement Sensor made from MEMS piezoresistive strain-sensor module was displayed on a force-sensing beam at the SAE World Congress and Exhibition from April 14 to April 17, 2008 in Detroit, MI.
4. In January 2008, the potential application of MEMS strain sensors and displacement sensors to bridge usage and health monitoring was discussed with representatives of the Army's Engineering Research and Development Center (ERDC-GSL-MS and ERDC-GSL-MS).
5. In December 2008, a test was conducted to monitor the loads from traffic on a public bridge using several bolt-on displacement sensors made from MEMS piezoresistive strain-sensor modules. The conducted test included both wired and wireless hook-up configurations (using Timken's wireless StatusCheck® 2.4 system). An accompanying report was issued on April 30, 2009 describing details of the conducted test.

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Calibration & Testing

**Developed under the
MEMS for Rolling-Element
Bearings Program**

July 30, 2010

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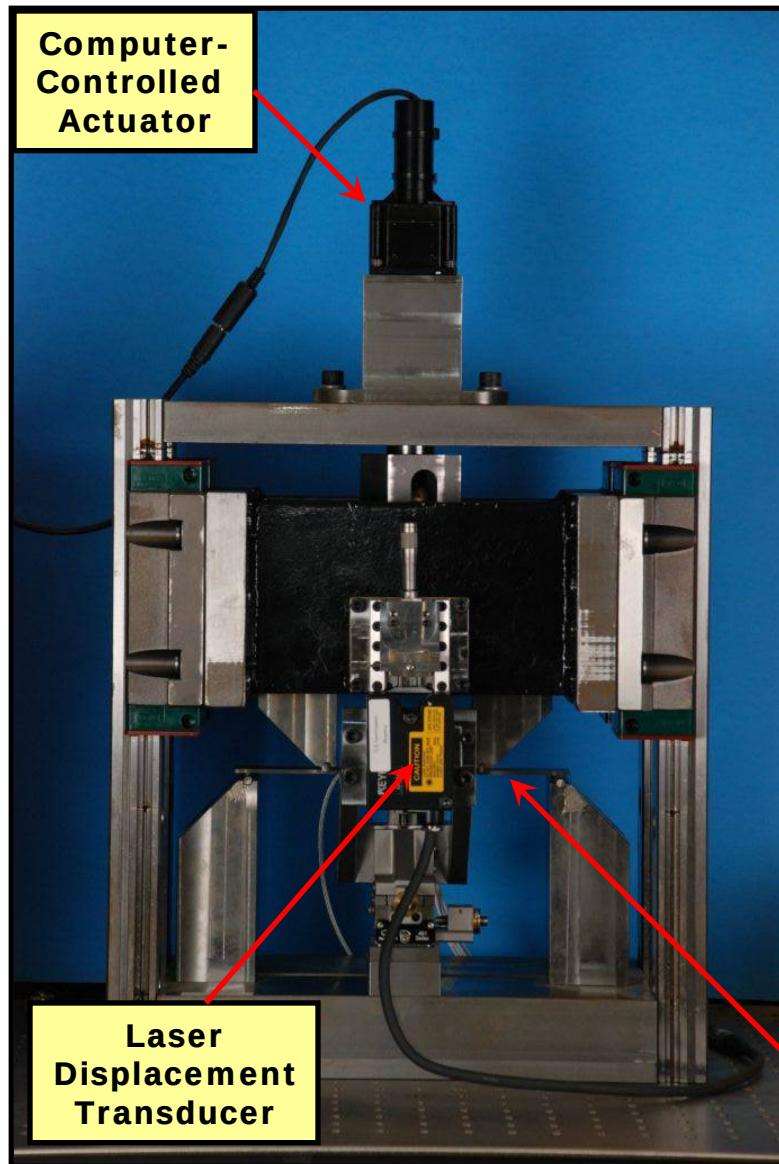
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Figure CT1: Four-point bending calibration / test system



Test Unit Main Features:

1. Computer-controlled actuation and data acquisition.
2. Applies static compressive or tensile strains to each of many sensors in the longitudinal or lateral sensor direction (ASTM Standard E855-90).
3. Switches between compressive or tensile strain with manual change.
4. Repeatability 10x to 20x better than other known units.

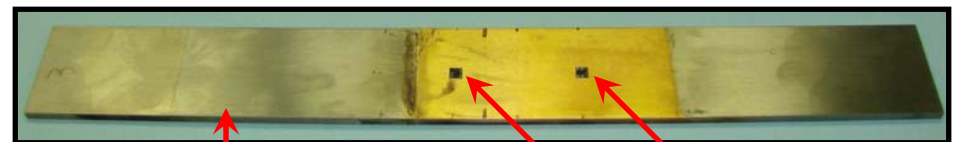
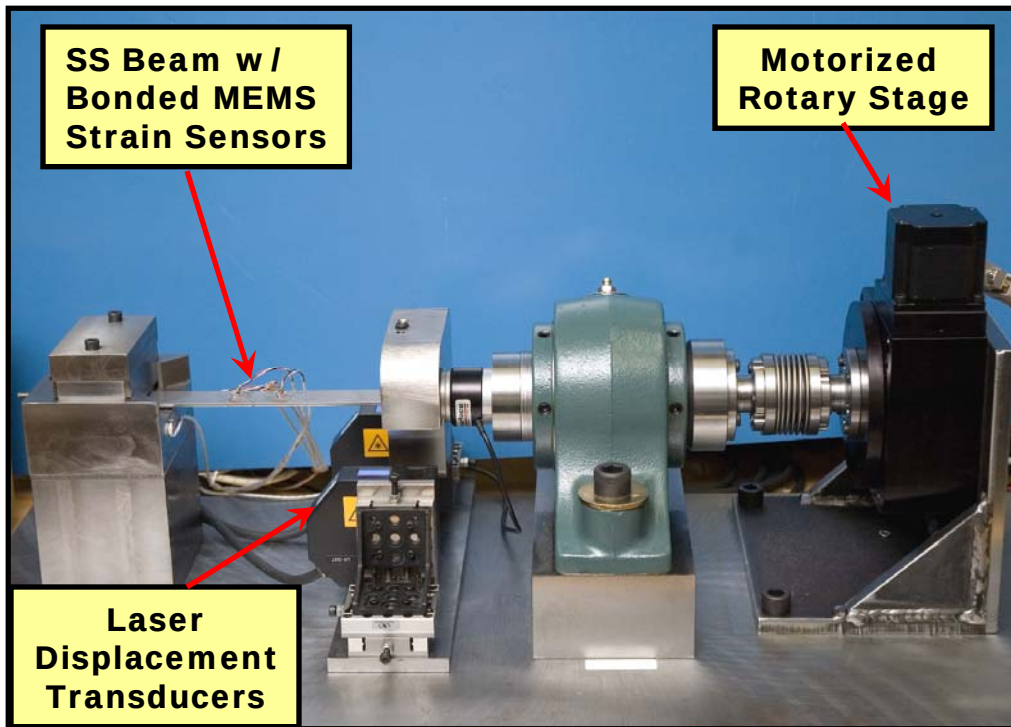


Figure CT2: Shear-strain calibration / test system

Test Unit Main Features:

1. Computer-controlled actuation and data acquisition.
2. Uses same beams (with sensors) as 4-point bending test system, therefore strain sensor response to applied longitudinal, lateral, and shear strains can be tested using both units in combination.
3. Sensors at 45° relative to beam long-axis to measure shear strain.
4. Capable of applying ± 30 N-m of torque.



FEA Modeling of SS Beam

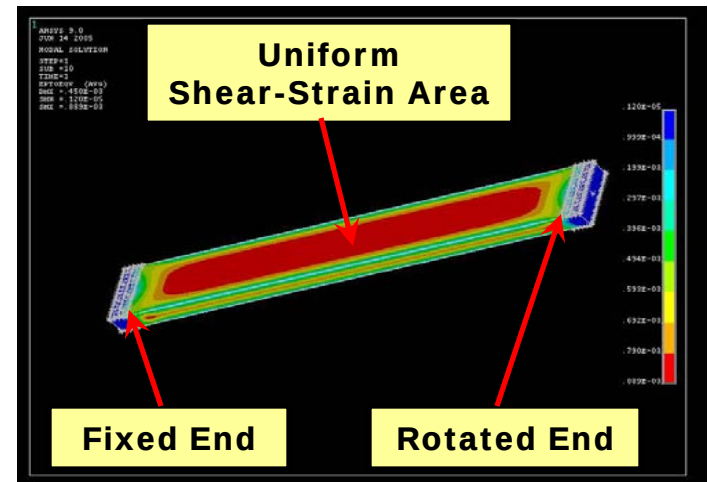
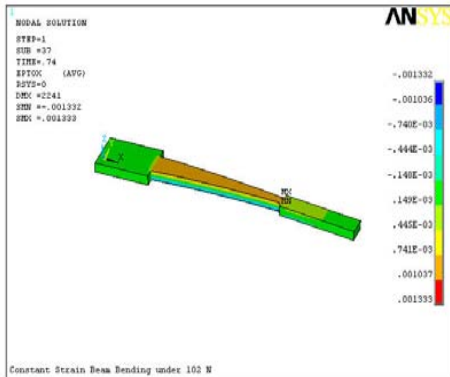


Figure CT3: Uniform-strain-beam calibration / test system

Test Unit Main Features:

- 1. Computer-controlled actuation and data acquisition.**
- 2. Uniform-strain-beam calibration / test system based on clamped-beam with large uniform-strain region (ASTM Standard E251-92).**
- 3. Applies compressive or tensile extensional strains to each sensor bonded on uniform-strain region.**
- 4. Can apply static and dynamic strains.**
- 5. Small size facilitates testing over entire temperature range.**



FEA of clamped-beam with large uniform-strain region



Uniform-strain beam configured for testing

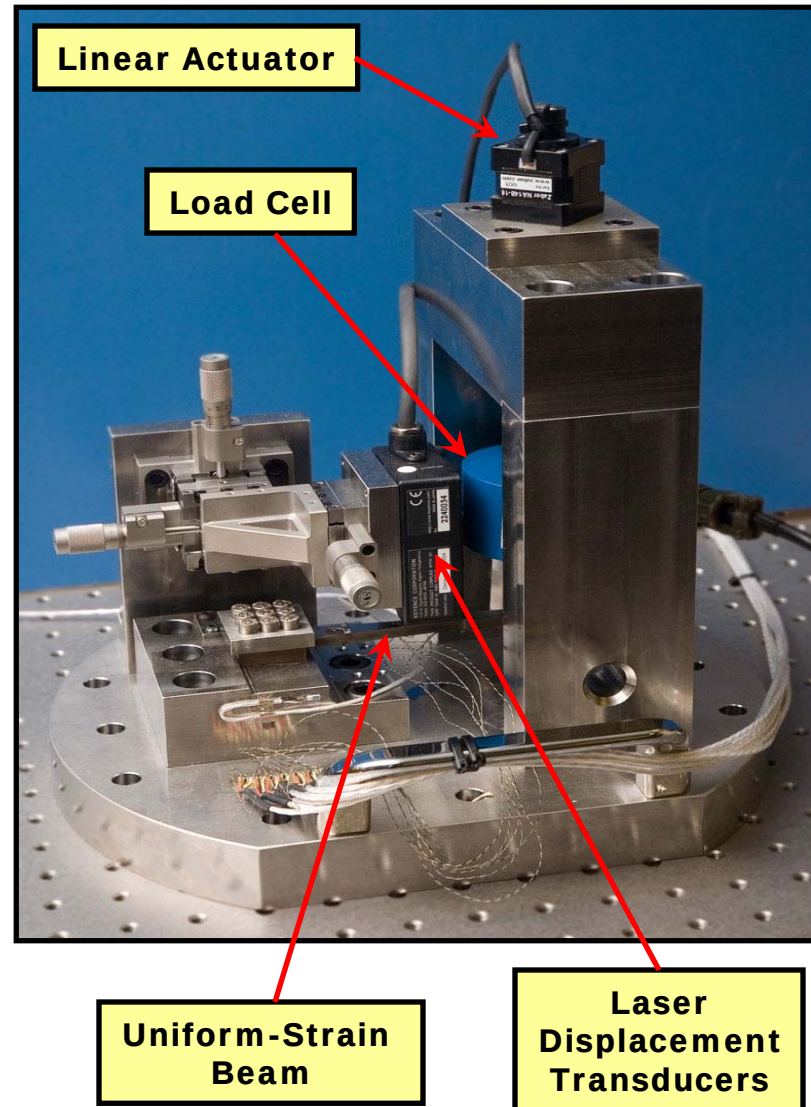


Figure CT4: Creep test stand for strain sensors

Test Unit Main Features:

- 1. Computer-controlled data acquisition with manual loading.**
- 2. Fits inside environmental chamber for testing over large temperature range (-55°C to 180°C)**

**Bonded Strain Sensors
On Uniform-Strain Beam**

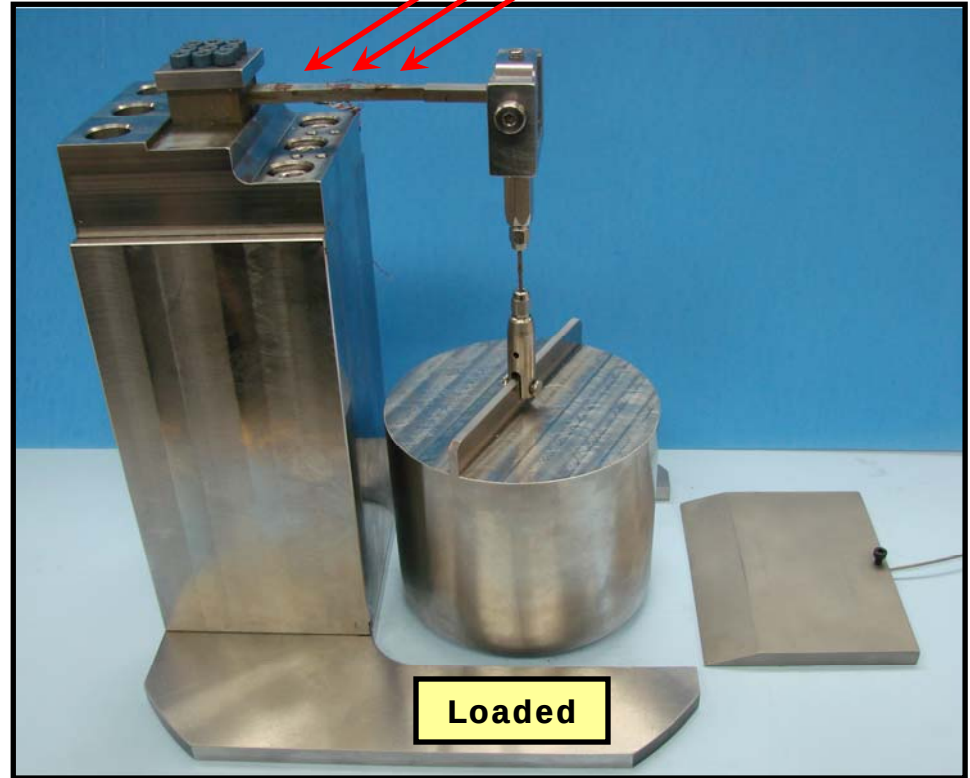


Figure CT5: Displacement sensor calibration / test system

Test Unit Main Features:

- 1. Automated control of static and dynamic displacements applied in the x, y, and z-directions (in any combination).**
- 2. Automated control of rotations applied about the x, y, and z-directions (in any combination).**
- 3. Multiple reference temperature sensors.**

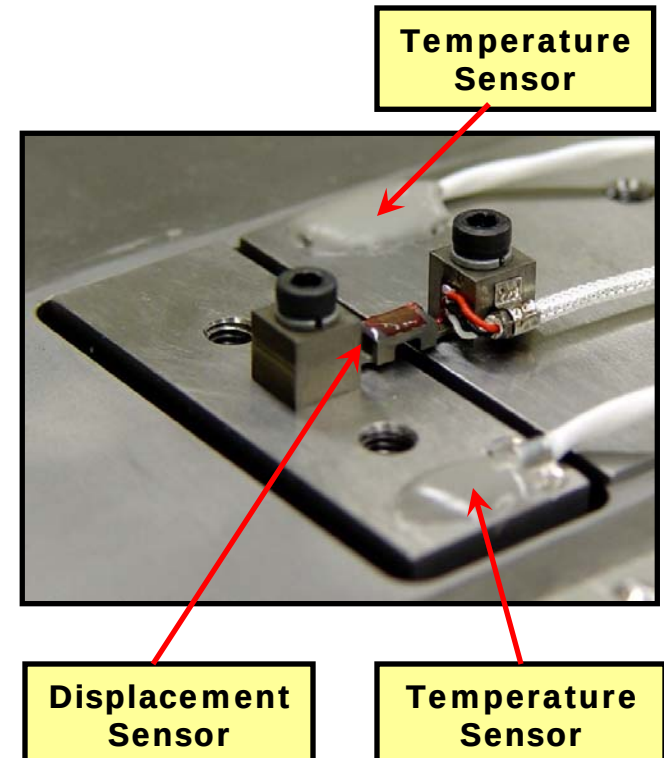
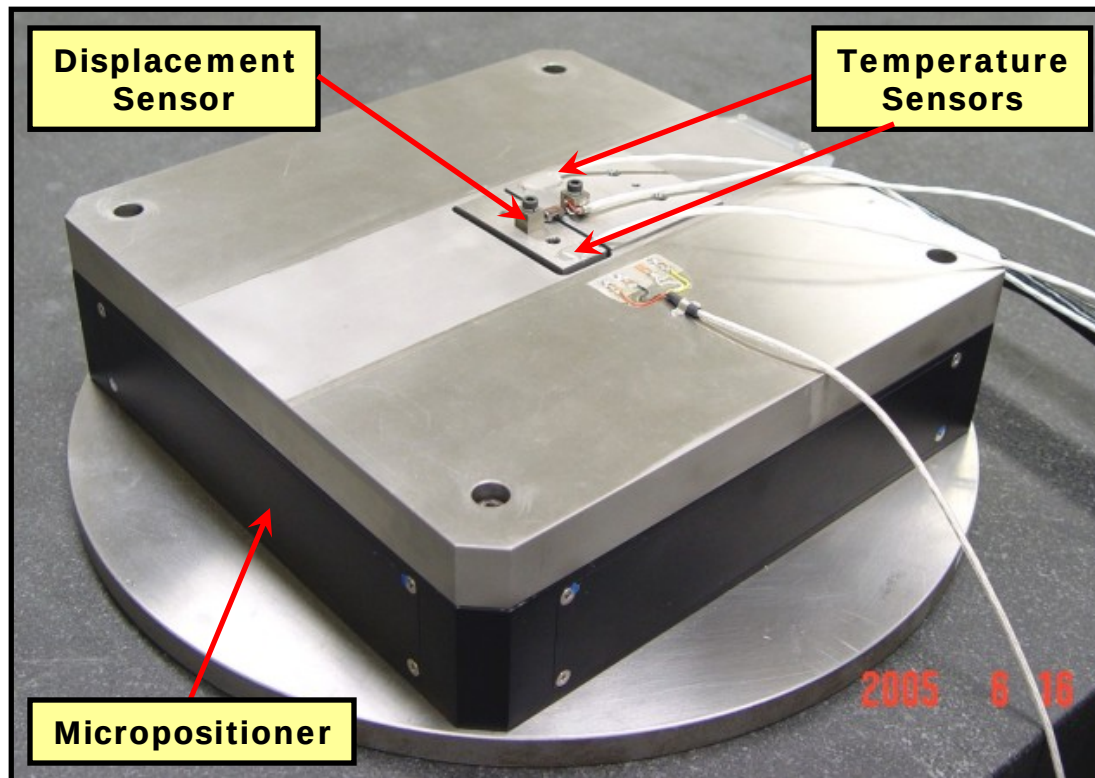


Figure CT6: Vibration test system

Test Unit Main Features:

- 1. Automated control and data acquisition.**
- 2. Vibrates displacement sensor in y and z-directions (with different fixtures) over the frequency band of 2 to 6,500 Hz.**

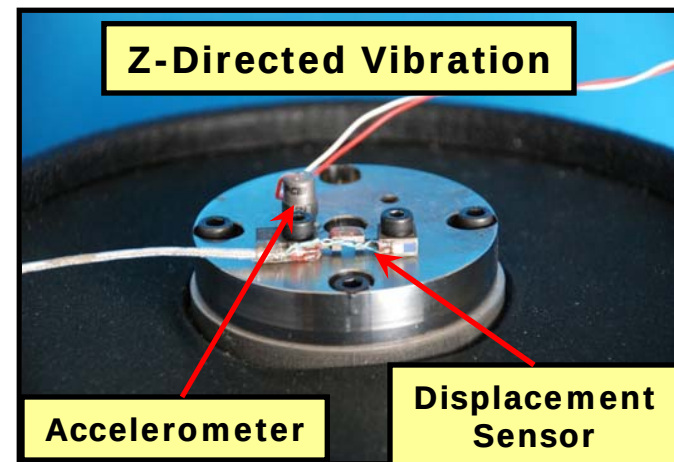
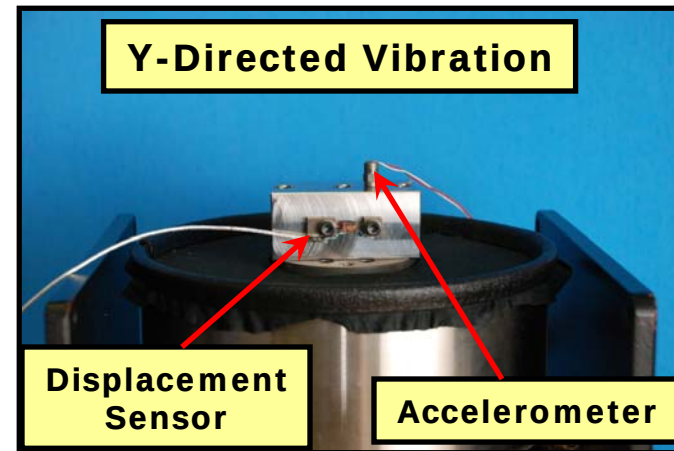
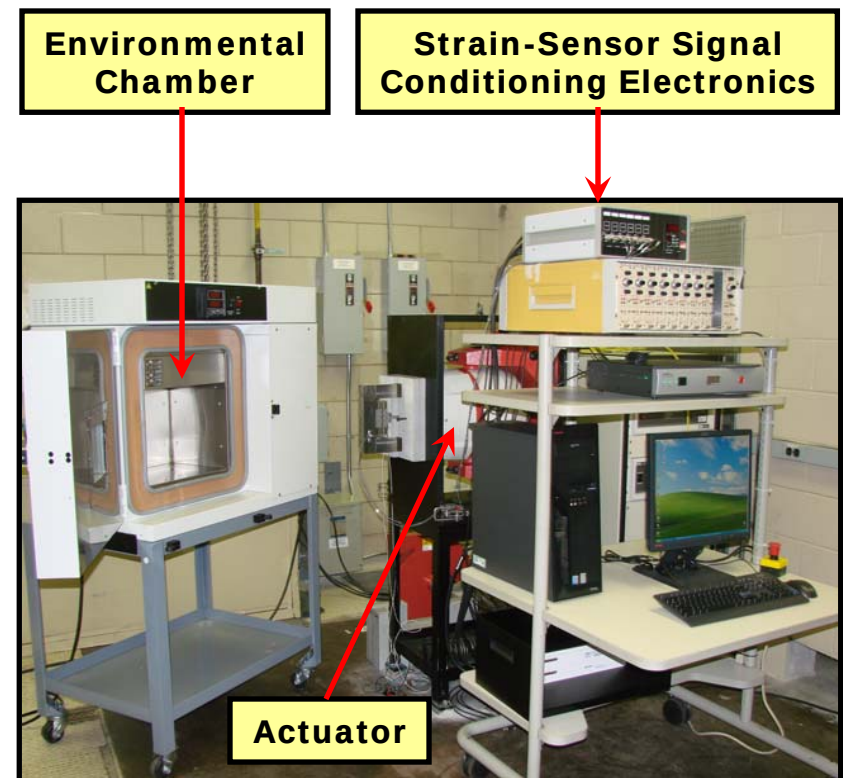
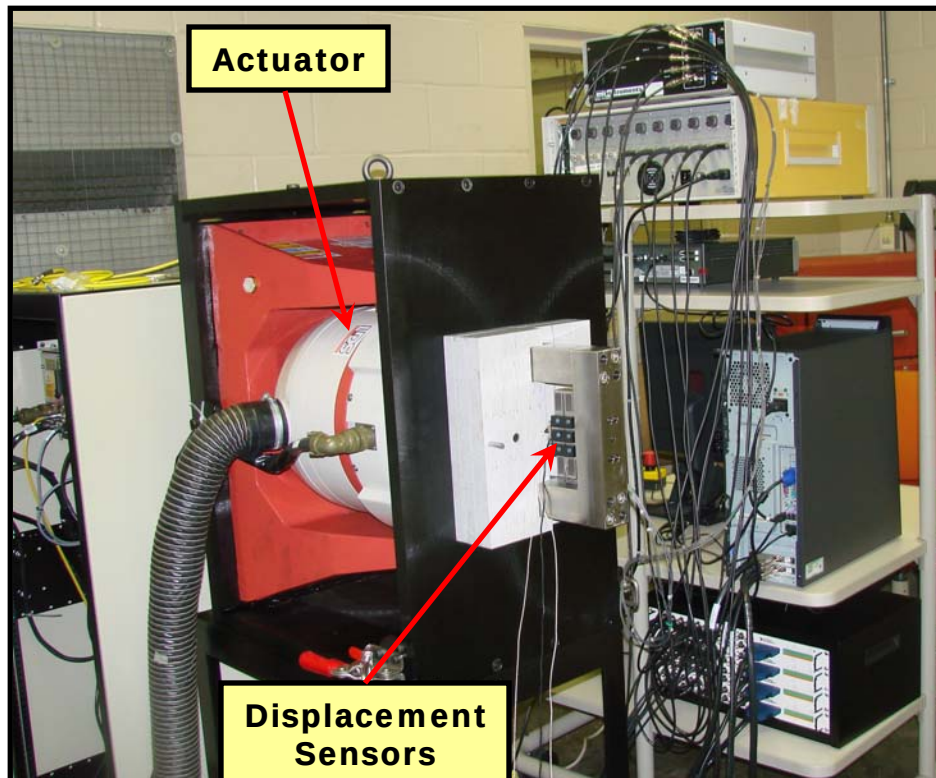


Figure CT7: Long-term performance test system

Test Unit Main Features:

- 1. Automated control and data acquisition.**
- 2. Simultaneously measures the performance of up to 6 displacement sensors at temperatures from -55°C to 180°C over the entire life of the sensors.**



Final Report - March 1, 2005 through April 30, 2010
MEMS for Rolling-Element Bearings Program (Proposal Number 48371-EG)

Program: MEMS for Rolling-Element Bearings
Project: Wireless Strain Monitoring
R&D by: The Timken Company

Objective:

The main objective of this project was to investigate the usefulness of the bolt-on displacement sensors in a wired and wireless data collection system on a bridge structure.

Approach:

Several bolt-on displacement sensors, described in other sections of this report, were integrated into wired and wireless sensor systems that were capable of measuring the strain/displacements (within a bridge structure) generated by applied loads (e.g., vehicles). Displacement sensors were attached to mounting fixtures that provided rapid non-intrusive attachment to the bridge using a clamping method. The wireless network was a modified version of Timken's StatusCheck[®] 2.4 data collection system. A signal-conditioning board was developed to adapt the MEMS displacement sensor signals to the signal processing and data collection board of StatusCheck[®] 2.4. The wireless system allowed rapid installation and data gathering compared with wired metal-foil strain-gauge systems currently on the market. Both wired and wireless sensor systems with integrated displacement sensors were tested on a public bridge.

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Significance:

Consistent monitoring of the structural health and usage of bridges and other structures provides less costly scheduled preventative maintenance. Rapid, low-cost installation of structural health and usage monitoring systems would be desirable compared to wired systems. Structural evaluation of buildings and bridges following a catastrophe could speed recovery efforts by providing rapid determinations of the soundness of structures and steps required to put the structure back into service. The benefits of rapid installation without major wiring can be applied to industrial process applications, transportation systems, buildings, and research and development efforts. The sensor/data collection nodes are battery powered with a battery life of up to 5 years, enabling long-term monitoring of structures.

Accomplishments:

Several MEMS displacement sensors were integrated with Timken's StatusCheck® 2.4 wireless data collection and communication network system (Figure WSM1). The displacement sensors used for this activity were developed and produced under other projects within this contract and their benefits are described in the corresponding project reports. The new integrated wireless system was tested and evaluated on a public bridge.

The wireless system (StatusCheck® 2.4) is a 2.4 GHz radio using an IEEE 802.15.4 physical layer radio with a proprietary network developed by Timken. Figure WSM2 summarizes the system main features. The Timken Network was developed previously to address the industrial environment and is well suited to the long narrow network geometries of bridges. A signal-conditioning board was developed to adapt the StatusCheck® 2.4 unit and generate power for the MEMS displacement sensors from a battery. Figure WSM3 summarizes the signal-conditioning board main features. The StatusCheck® 2.4 collects data, parameterizes the data set, and transmits peak, standard deviation, and mean for strains/displacements, ambient temperature and device temperature from the data set. This reduces transmission time and energy allowing for more frequent transmissions or longer service life.

A public bridge close to Timken's Technology Center – North Canton (Figure WSM4) was selected for the testing and evaluation of the new integrated StatusCheck® 2.4 wireless system. A non-intrusive mounting system was designed and produced to allow for rapid installation of the displacement sensors. The developed mounting system enables mounting without drilling into the structure (e.g., bridge) and increases the area under evaluation limiting the effects of localized imperfections. It also reduces surface preparation and restoration after sensor removal (Figure WSM5).

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Prior to implementation of the developed wireless system, a preliminary test using a wired displacement-sensor system was conducted in order to evaluate the sensor non-intrusive mounting system and the sensitivity of displacement sensors to bridge loads generated by the passing vehicles. Wired metal-foil displacement sensors and MEMS displacement sensors were mounted on three center I-beams of the bridge (Figure WSM6). The mounting hardware and procedures for the sensors yielded measurable results with known and unknown vehicle loads traversing the bridge. Figure WSM7 shows sample results from the preliminary field test on the Gambrinus Avenue Bridge (August 14, 2008). Large transient signals due to the passage of vehicles are clearly visible. Larger amplitudes indicate heavier vehicles. Shorter transients indicate faster vehicles.

A test using the modified StatusCheck® 2.4 devices with integrated MEMS piezoresistive displacement sensors was conducted on the Gambrinus Bridge on December 3, 2008. Data from the first test indicated significant variance in the flatness of the bridge beams and therefore the original mounting system was modified to accommodate for this variance. On each modified mounting fixture, three displacement sensors were attached (Figures WSM8 & WSM9) as follows:

1. A metal-foil displacement sensor wired to remotely located signal-conditioning electronics
2. A MEMS displacement sensor wired to remotely located signal-conditioning electronics
3. A MEMS displacement sensor integrated with the StatusCheck® 2.4 wireless system

The test included a fifteen-ton truck (Figure WSM10) moving to known positions on the bridge in the south bound then north bound lanes. The truck stopped for ten seconds at each location to allow the StatusCheck® 2.4 at least two data points per position, the StatusCheck® 2.4 transmission period was set to four seconds. The truck then passed over the south bound then north bound lanes at forty miles per hour. The static test demonstrated good correlation between the StatusCheck® 2.4 data and standard data collection systems. Figure WSM11 shows sample results from the dynamic test using the StatusCheck® 2.4 system. The StatusCheck® 2.4 collected data for 1 second out of every 4 seconds, with the other 3 seconds reserved for processing and communications.

Conclusions:

The above developmental efforts and obtained test results have clearly demonstrated the usefulness of the bolt-on displacement sensors in a wired and wireless data collection system implemented on a public bridge structure. The static test demonstrated good correlation between the StatusCheck® 2.4 data and standard data collection systems in detecting the weight of vehicles and their passage in traffic.

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Technology Transfer:

During the MFREB program duration, several progress reports and program presentations related to this project were presented to members of ARO and ARL as follows:

1. August 31, 2008 – Annual progress report
2. December 31, 2008 – Interim progress report
3. March 26, 2009 – Program presentation
4. April 30, 2009 – Interim progress report
5. August 31, 2009 – Annual progress report
6. July 30, 2010 – Final program presentation
7. July 30, 2010 – Final program report

In January 2008, the potential application of MEMS strain-sensors and displacement sensors to bridge usage and health monitoring was discussed with representatives of the Army's Engineering Research and Development Center (ERDC-GSL-MS and ERDC-GSL-MS).

In December 2008, a test was conducted to monitor the loads from traffic on a public bridge using several bolt-on displacement sensors made from MEMS piezoresistive strain-sensor modules. The conducted test included both wired and wireless hook-up configurations (using Timken's wireless StatusCheck® 2.4 system). An accompanying report was issued on April 30, 2009 describing details of the conducted test.

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Wireless Strain Monitoring

Developed under the
MEMS for Rolling-Element
Bearings Program

July 30, 2010

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Figure WSM1: Integration of MEMS displacement sensor w/ StatusCheck® 2.4

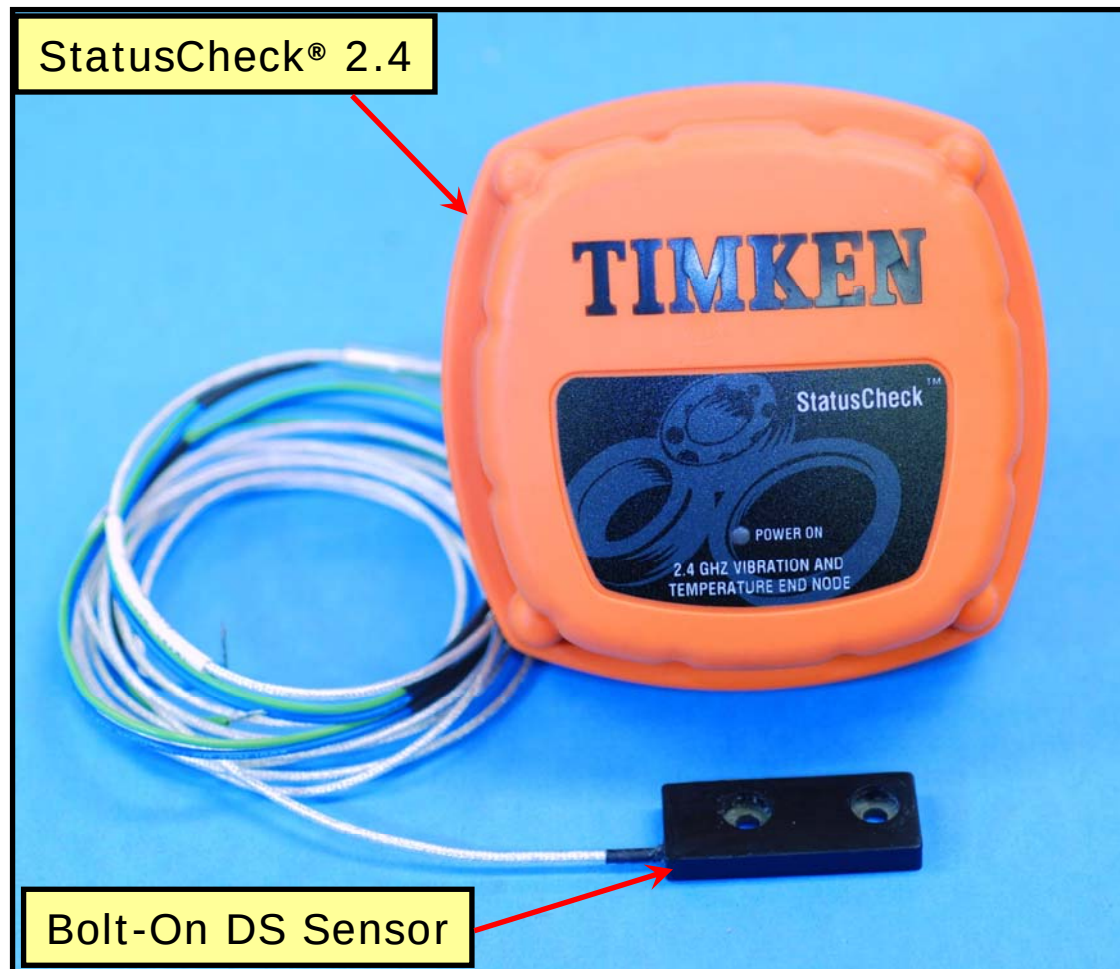
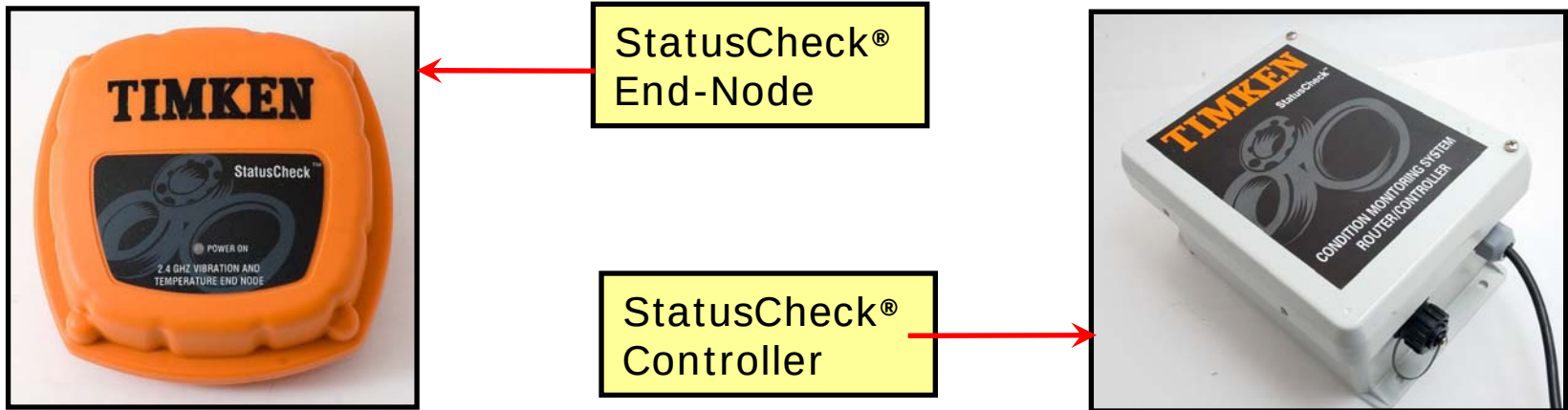


Figure WSM2: Main features of Timken StatusCheck® 2.4 wireless system



1. Low-power, battery-operated (3V) wireless system
2. FCC approved 2.4 GHz radio transmitter
3. Adjustable transmission rate (four choices)
4. Transmission range: 1 km (0.5 mile) line-of-sight
5. Cluster tree network monitors up to 100 end-nodes
6. Spring loaded RTD temperature probe
7. Two-axis vibration measurements (0 – 18G)
8. Ambient temperature compensation
9. Customizable software interface
10. Controller/PC records data and provides visual reporting
11. User-defined thresholds can be established to trigger alerts
12. Magnetic or threaded mounting options
13. Compact size: 97 mm x 100 mm x 58 mm (3.82" x 3.94" x 2.28")

Figure WSM3: Signal-conditioning board for MEMS displacement sensor

Main Features of SG-24 Signal-Conditioning Board:

1. Power source for MEMS displacement sensor
2. Sensor signal filtering
3. Sensor preload adjustment
4. Offset adjustment
5. Gain adjustment
6. Temperature signal conditioning
7. Battery powered (3V) wireless system

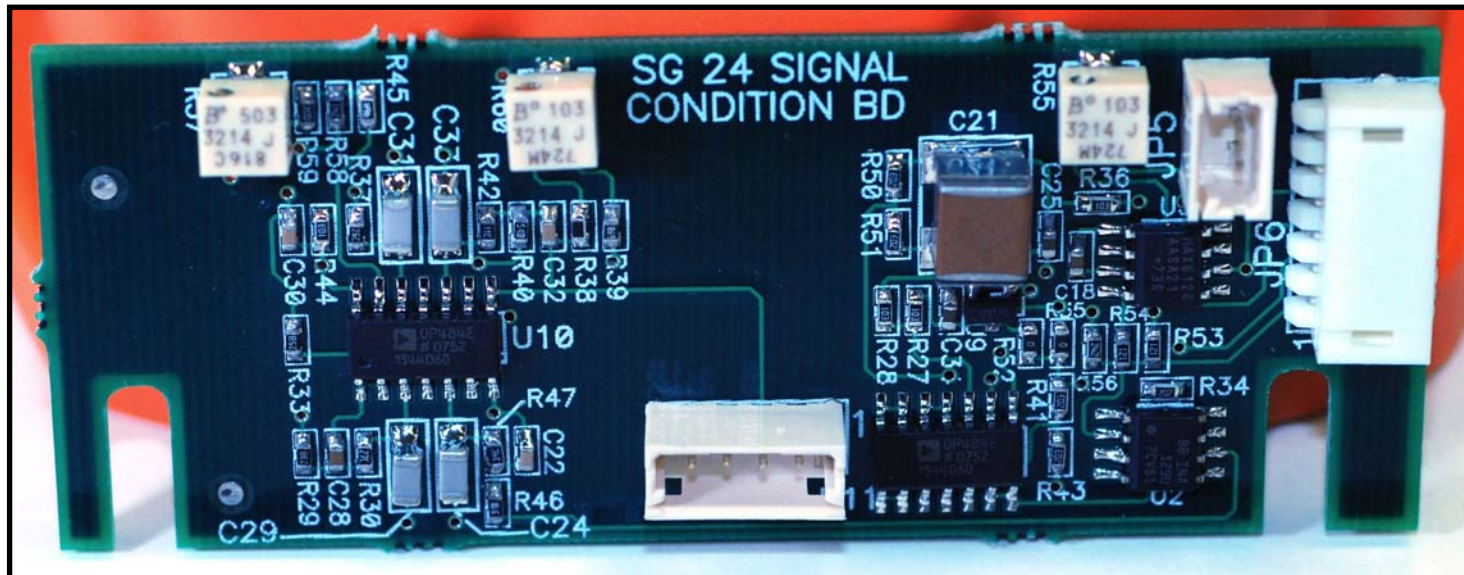
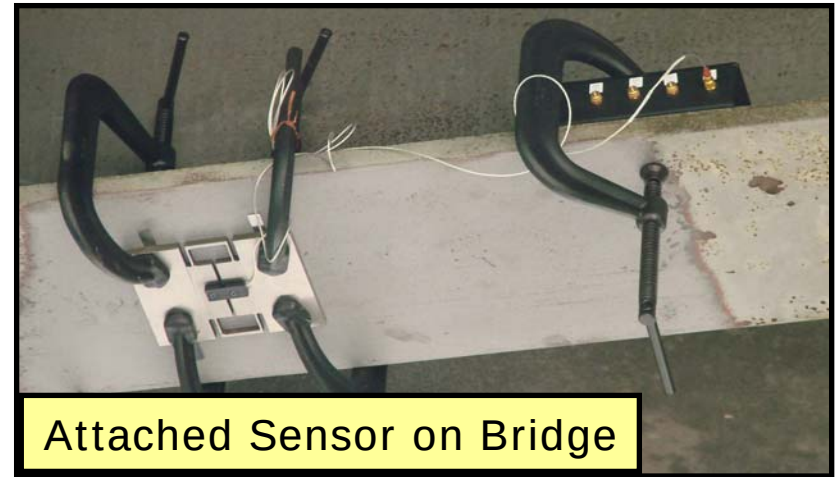
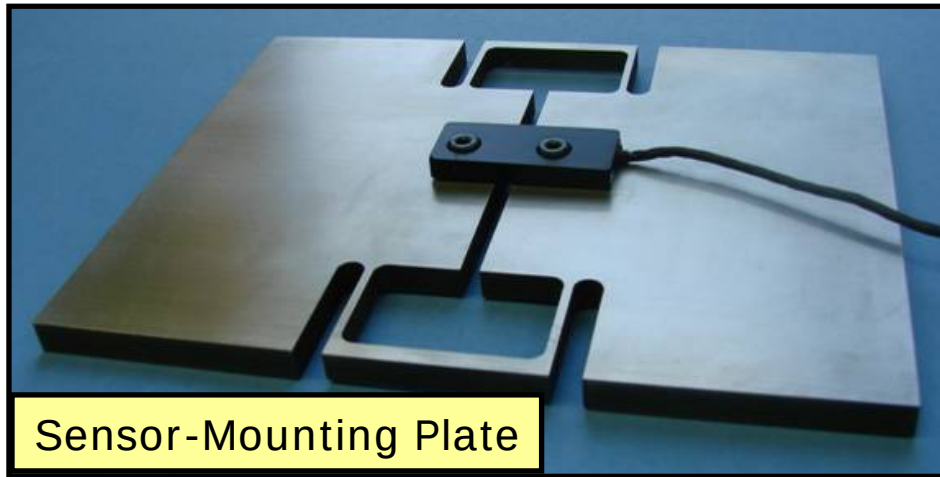


Figure WSM4: Gambrinus Bridge – 8/14/2008



Figure WSM5: Installation of displacement sensor on Gambrinus Bridge – 8/14/2008



- 1. Metal-foil and MEMS piezoresistive strain gauges were adhesively bonded to steel substrates of bolt-on displacement sensors.**
- 2. The bolt-on displacement sensors were bolted on specially designed non-invasive mounting plates.**
- 3. The mounting-plate design provided a non-intrusive clamping surface for sensor installation on the bridge and effectively increased the strain gauge length.**
- 4. The non-invasive mounting plates with bolted displacement sensors were attached with C-clamps on three bridge I-beams for strain / displacement measurements.**
- 5. The bridge-attached displacement sensors were wired directly to data acquisition hardware.**

Figure WSM6: Preliminary field test on Gambrinus Bridge – 8/14/2008

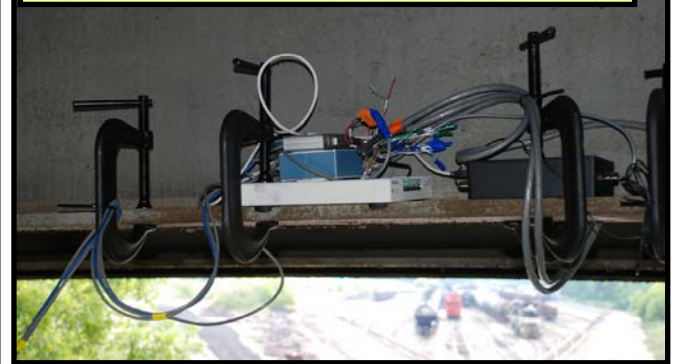
Surface Preparation



Mounting Plate Attachment



Data Acquisition Hardware



29.9k Lbs Test Truck

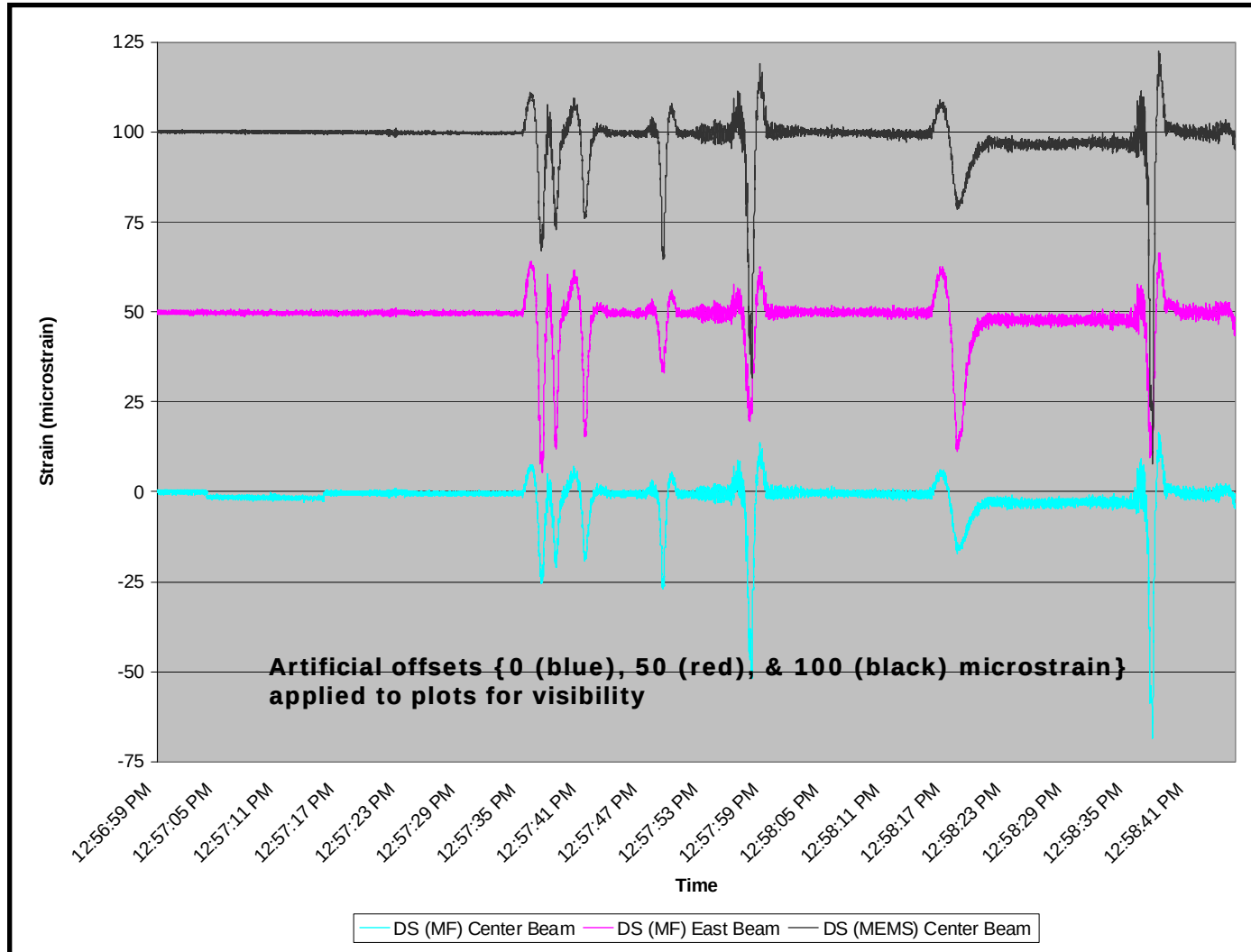


Track Position w/ Laser Range Finder



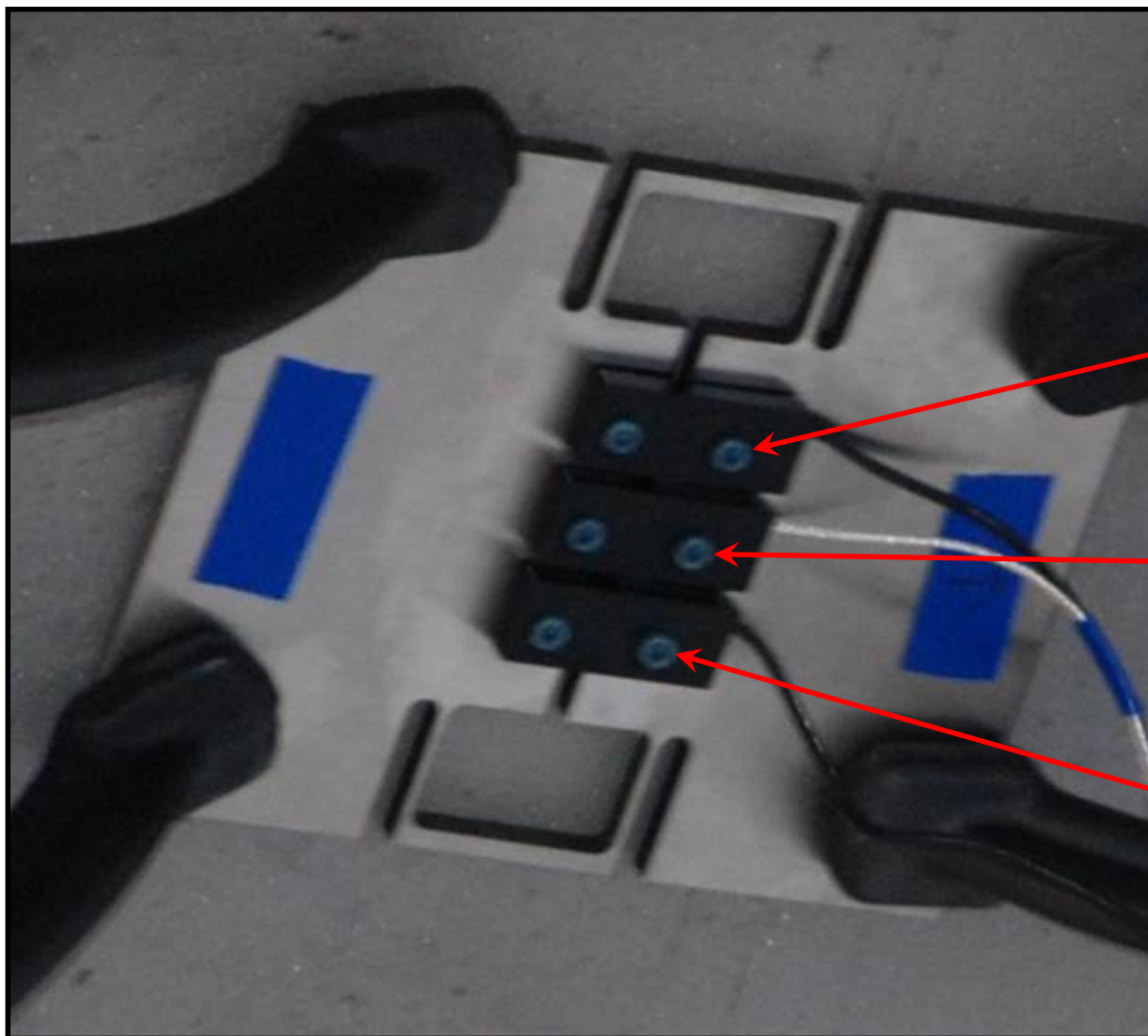
Conducted Tests: Two static and two dynamic tests, one in each lane

Figure WSM7: Sample results from field test on Gambrinus Bridge – 8/14/2008



Preliminary Test Results: Large transient signals due to the passage of vehicles are clearly visible. Larger amplitudes indicate heavier vehicles. Shorter widths of transients indicate faster vehicles.

Figure WSM8: DS assembly for field test on Gambrinus Bridge – Dec. 3, 2008



**MEMS Displ-Sensor
wired to signal
conditioning electronics**

**Metal-foil Displ-Sensor
wired to signal
conditioning electronics**

**MEMS Displ-Sensor
integrated w/
StatusCheck® 2.4 for
wireless data
transmission**

Figure WSM9: DS assembly installation on Gambrinus Bridge – 12/3/2008

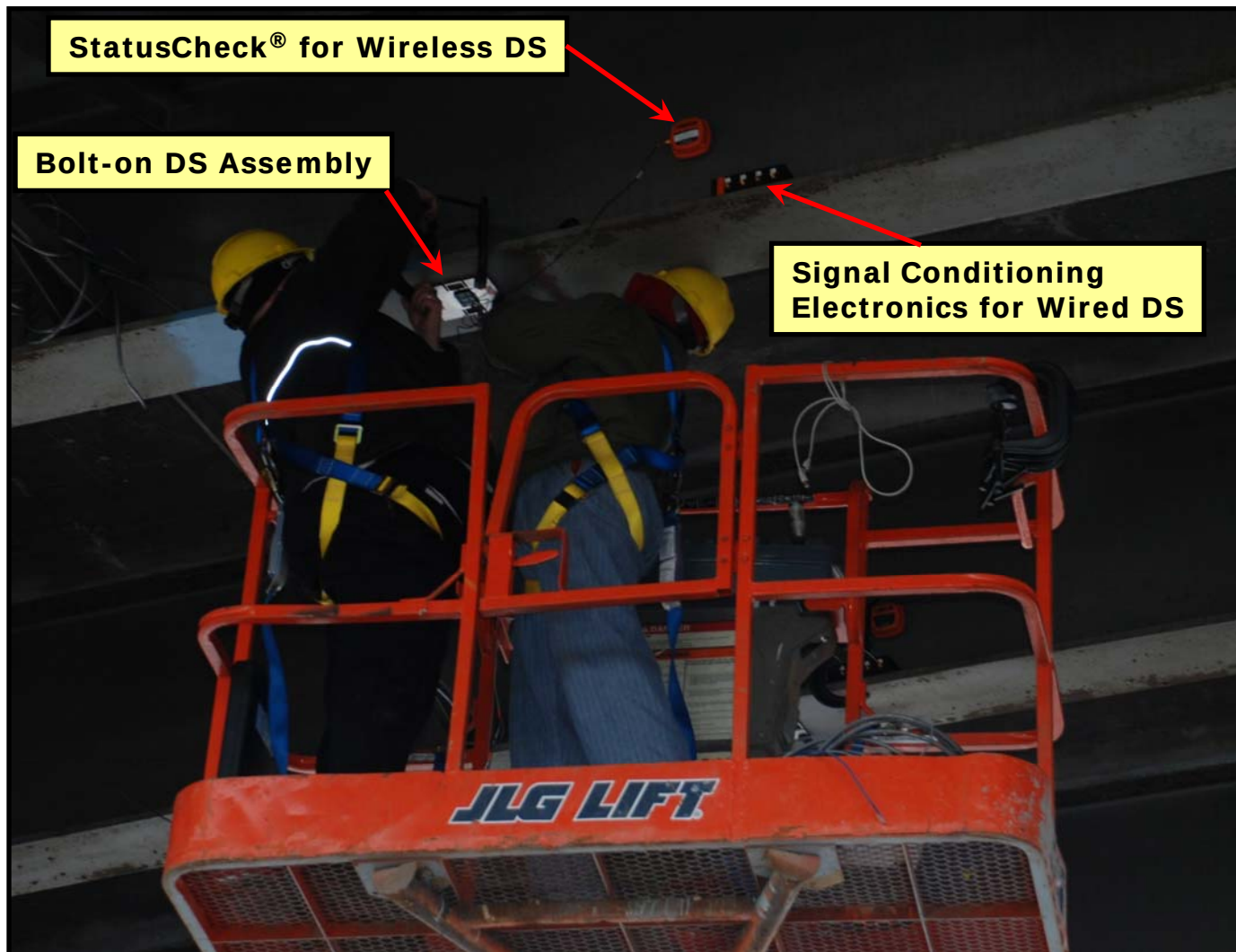
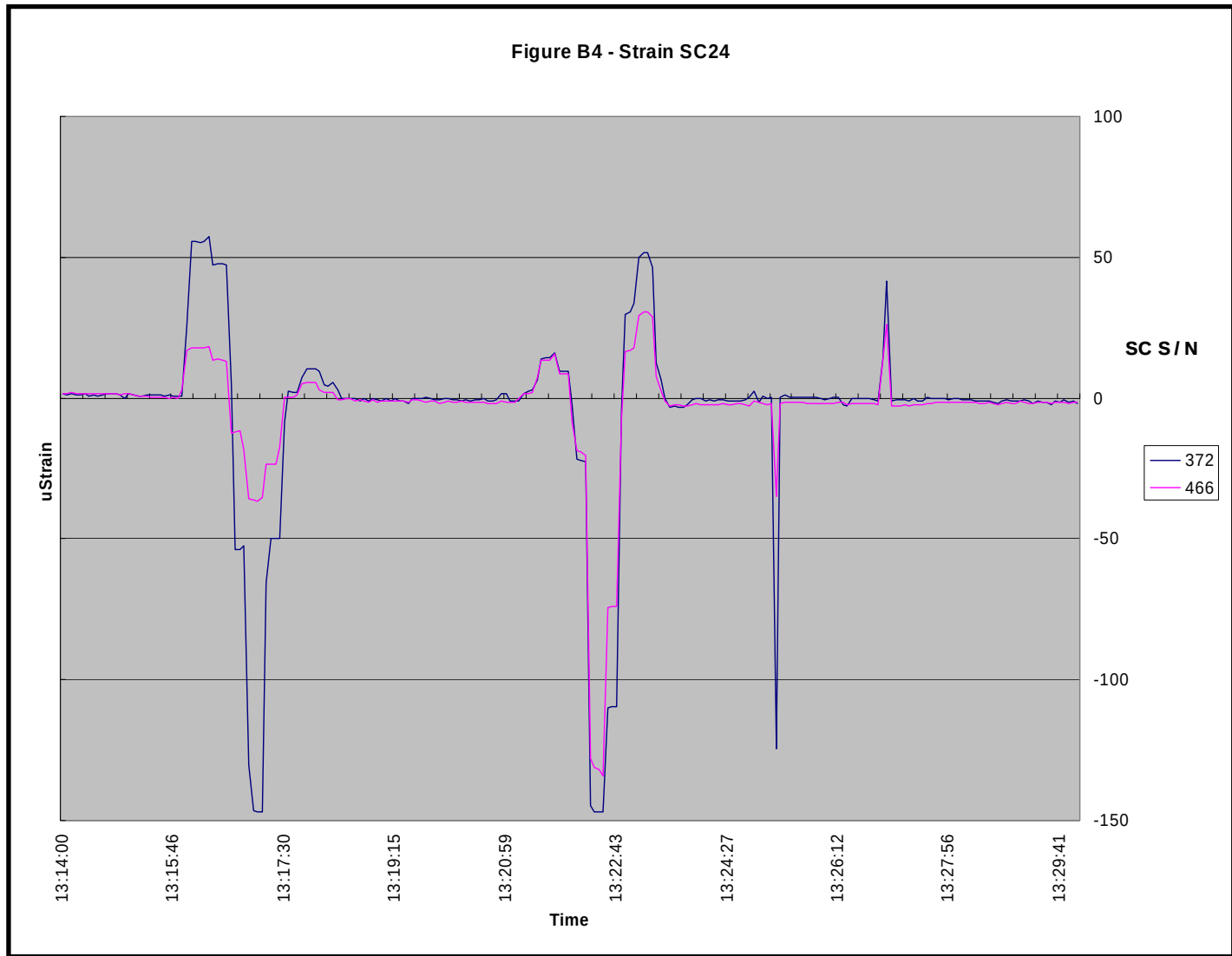


Figure WSM10: Conducted field test on Gambrinus Bridge – 12/3/2008



Track Position w/ Laser Range Finder

Figure WSM11: Strain data sample from field test on Gambrinus Bridge – 12/3/2008



Bridge Strain Data with StatusCheck-Integrated MEMS DS:

Each data point displayed is the peak value of 1 second of collection out of a 4 second interval. A 150 Hz filter is used in the data collection system.