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Title: **Automated Health Monitoring of Rail Cars and Railroad Bridges Using Embedded Sensors**

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ABSTRACT

Current maintenance operations and integrity checks on a wide array of structures require personnel entry into normally-inaccessible or hazardous areas to perform necessary nondestructive inspections. To gain access for these inspections, structure must be removed, sealant must be removed, disassembly processes must be completed, or personnel must be transported to remote locations. The use of in-situ sensors, coupled with remote interrogation, can be employed to overcome a myriad of inspection impediments stemming from accessibility limitations, complex geometries, the location and depth of hidden damage, and the isolated location of the structure. Furthermore, prevention of unexpected flaw growth and structural failure could be improved if on-board health monitoring systems were used to more regularly assess structural integrity. Reliable Structural Health Monitoring (SHM) systems can automatically process data, assess structural condition, and signal the need for specific maintenance actions. A research program has been completed to develop and validate Comparative Vacuum Monitoring (CVM) Sensors for surface crack detection. The test specimens included those designed to simulate crack origination sites on aircraft and bridge structures. The test matrix studied the affects of surface coating, skin thickness, and material type on the performance of the CVM sensors. Statistical methods using one-sided tolerance intervals were employed to derive Probability of Detection (POD) levels for each of the test scenarios. The result is a series of flaw detection curves that can be used to propose CVM sensors for crack detection. Complimentary, multi-year field tests were also conducted to study the deployment and long-term operation of CVM sensors on aircraft and bridges. This paper presents the quantitative crack detection capabilities of the CVM sensor, its performance in actual operating environments, and the prospects for structural health monitoring applications on a wide array of civil structures.

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INTRODUCTION

Multi-site fatigue damage and hidden cracks in hard-to-reach locations are among the major flaws encountered in today's extensive array of aging structures and mechanical assemblies. The costs associated with the increasing maintenance and surveillance needs of aging structures are rising. The application of Structural Health Monitoring (SHM) systems using distributed sensor networks can reduce these costs by facilitating rapid and global assessments of structural integrity. These systems also allow for condition-based maintenance practices to be substituted for the current time- or cycle-based maintenance approaches thus optimizing maintenance labor [1]. Other advantages of on-board, distributed sensor systems are that they can eliminate costly, and potentially damaging, disassembly, improve sensitivity by producing optimum placement of sensors with minimized human factors concerns in deployment and decrease maintenance costs by eliminating more time-consuming manual inspections. Current structural maintenance operations require personnel entry into normally-inaccessible or hazardous areas to perform mandated, nondestructive inspections. These processes are not only time consuming but they provide the opportunity to induce damage to the structure. The use of in-situ sensors for monitoring the condition of structures and mechanisms, coupled with remote interrogation, can be employed to overcome inspection difficulties including the remote location and expansive distribution of critical structures such as railway bridges and rail cars. Prevention of unexpected flaw growth and structural failure could be improved if on-board health monitoring systems are used to more regularly assess structural integrity [2, 3]. The ease of monitoring an entire network of distributed sensors means that structural health assessments can occur more often, allowing operators to be even more vigilant with respect to flaw onset.

Comparative Vacuum Monitoring

Comparative Vacuum Monitoring (CVM) is a simple pneumatic sensor technology developed to detect the onset of cracks. CVM sensors are permanently installed to monitor critical regions of a structure. The CVM sensor is based on the principle that a steady state vacuum, maintained within a small volume, is sensitive to any leakage [4]. A crack in the material beneath the sensor will allow leakage resulting in detection via a rise in the monitored pressure. Figure 1 shows top-view and side-view schematics of the self-adhesive, elastomeric sensors with fine channels etched on the adhesive face along with a sensor being tested in a lap joint panel. When the sensors are adhered to the structure under test, the fine channels and the structure itself form a manifold of galleries alternately at low vacuum and atmospheric pressure. Vacuum monitoring is applied to small galleries that are placed adjacent to the set of galleries maintained at atmospheric pressure. If a flaw is not present, the low vacuum remains stable at the base value. If a flaw develops, air will flow from the atmospheric galleries through the flaw to the vacuum galleries. When a crack develops, it forms a leakage path between the atmospheric and vacuum galleries, producing a measurable change in the vacuum level. This change is detected by the CVM monitoring system shown in Figure 2. It is important to note that the sensor detects surface breaking cracks once they interact with the vacuum galleries. Since the sensor physics is based on pressure measurements, there is no electrical excitation involved. These sensors can be attached to a structure in areas where crack growth is known to occur. On a pre-established engineering interval, a reading will be taken from an easily accessible point on the structure.

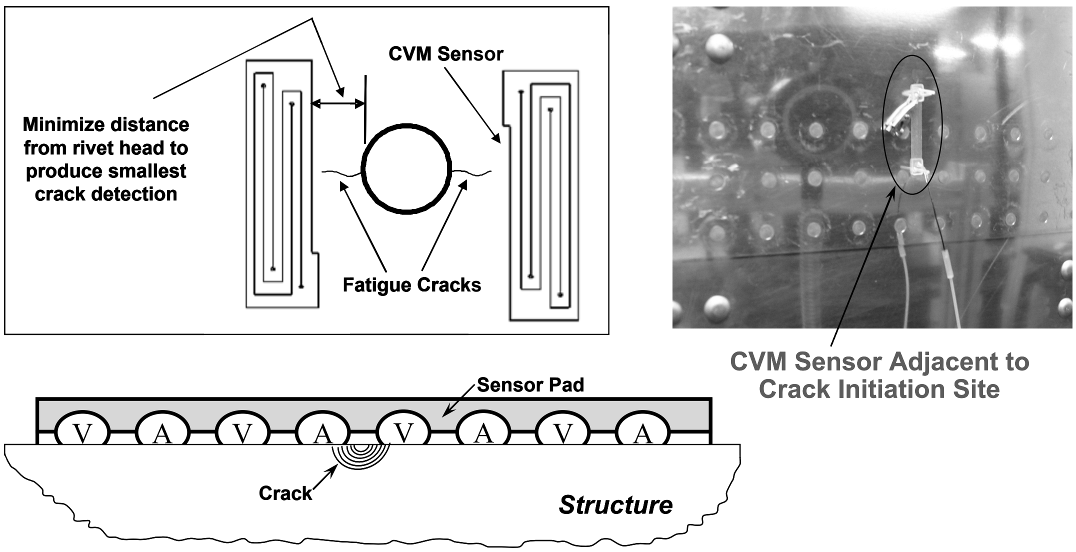

Figure 1: Schematics Depicting Operation of CVM Sensor and Polymer Sensor Mounted on the Outer Surface of a Riveted Lap Joint

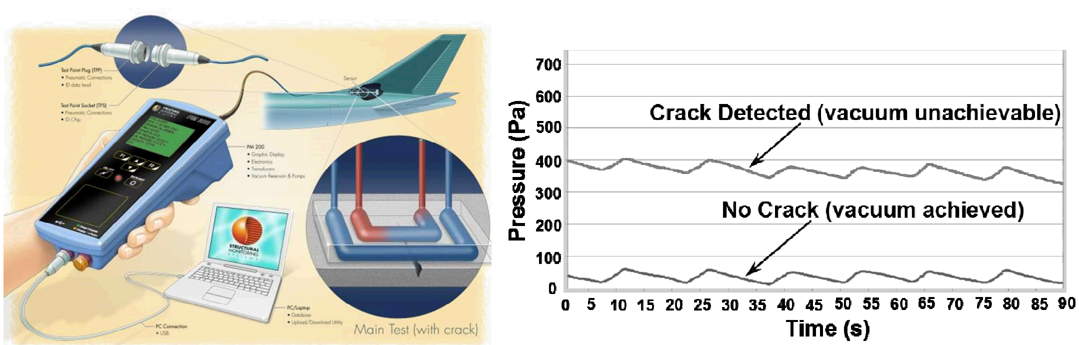

Figure 2: Crack Detection Monitoring with CVM System and Pressure Response Used to Indicate the Presence of a Crack

Applications for Crack Detection Using CVM Sensors

Recent events have demonstrated the need to address critical infrastructure surety needs [5]. The applications for CVM sensors can include such diverse structures as: buildings, bridges, trains and subway vehicles, mining structures, railroad cars, trucks and other heavy machinery, pressure vessels, oil recovery equipment, pipelines, steel transmission towers, ships, tanks and a wide array of military structures. Damage can arise from service loads as well as from external impact, off-design conditions or malevolent attacks.

In the matter of bridge refurbishment alone, the National Bridge Inventory Database (Fed. Highway Admin. 2003) indicates that 30% of the 600,000 bridges in the United States are "structurally deficient." In addition, a majority of the rail bridges in U.S. are operating beyond their initial design life. A bridge that is "structurally deficient" is still strong enough and stable enough for use; however, closer scrutiny of the bridge is required to ensure its continued, safe operation. In 2006, the American Society of Civil Engineers (ASCE) issued a report on the status of the U.S. infrastructure. It assessed everything from roads to hazardous waste systems and gave the country's infrastructure an overall grade of "D". Steel superstructure bridges built during the interstate construction boom of the 1950s and 1960s are reaching or surpassing their initial design lifetime. Depending on their level of maintenance, some bridges are showing visible signs of deterioration. On September 30, 2006, part of an overpass collapsed in Laval, a suburb of Montreal. On August 1, 2007 an Interstate 35 bridge crossing the Mississippi River in Minneapolis failed. The collapse of the Interstate 35 bridge prompted many questions regarding the health of similar structures around the world and their associated maintenance programs. Figure 3 shows three bridge failures – in Minneapolis, Montreal and Connecticut – and one bridge in Delaware with a large fatigue crack that was discovered and repaired prior to any catastrophic failure.

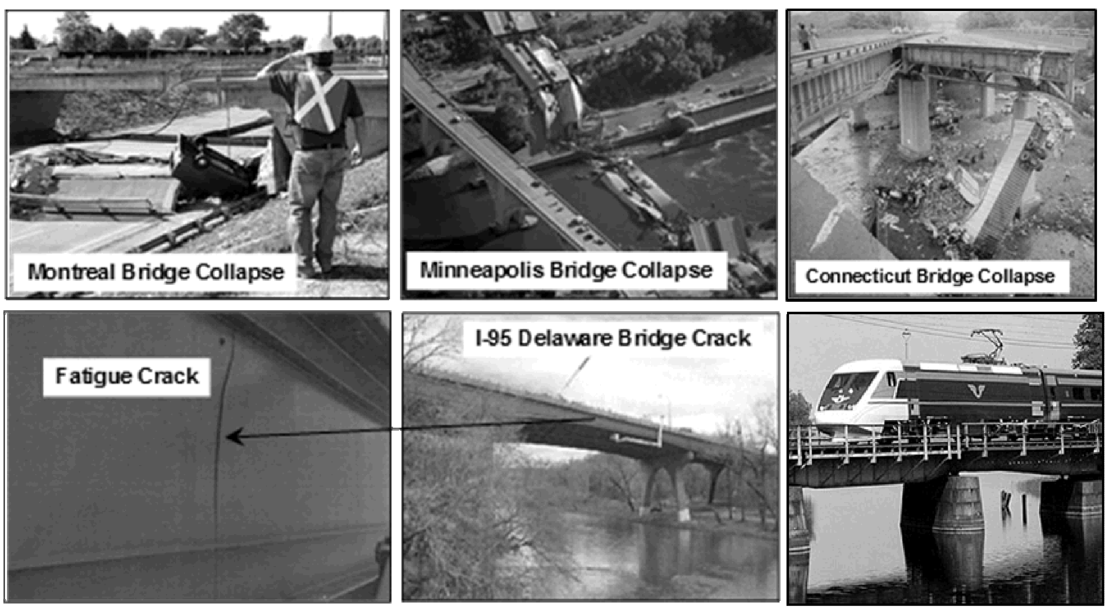

Figure 3: Applications for In-Situ Crack Detection Using CVM Sensors

CVM Performance Assessment Using One-Sided Tolerance Intervals

The Federal Aviation Administration's Airworthiness Assurance Center at Sandia Labs, in conjunction with industry and airline partners, completed validation testing on the CVM system in an effort to adopt Comparative Vacuum Monitoring as a standard NDI practice [5-6]. Fatigue tests were completed on aircraft components to grow cracks in representative structure while the vacuum pressures within the various sensor galleries were simultaneously recorded. A fatigue crack was propagated until it engaged one of the vacuum galleries such that crack detection was achieved and the sensor indicated the presence of a crack by its inability to maintain a vacuum. Probability of flaw detection assessments were coupled with on-aircraft flight tests to study the performance, deployment, and long-term operation of CVM sensors on aircraft. The result was a series of flaw detection curves that can be used to propose CVM sensors for aircraft crack detection. One set of test specimens were wing box fittings from the Boeing 737 which was the chosen CVM application from Delta Air Line’s fleet. Figure 4 shows the details of one test series addressing a wing box fitting application along with installation of CVM sensors for the flight test program.

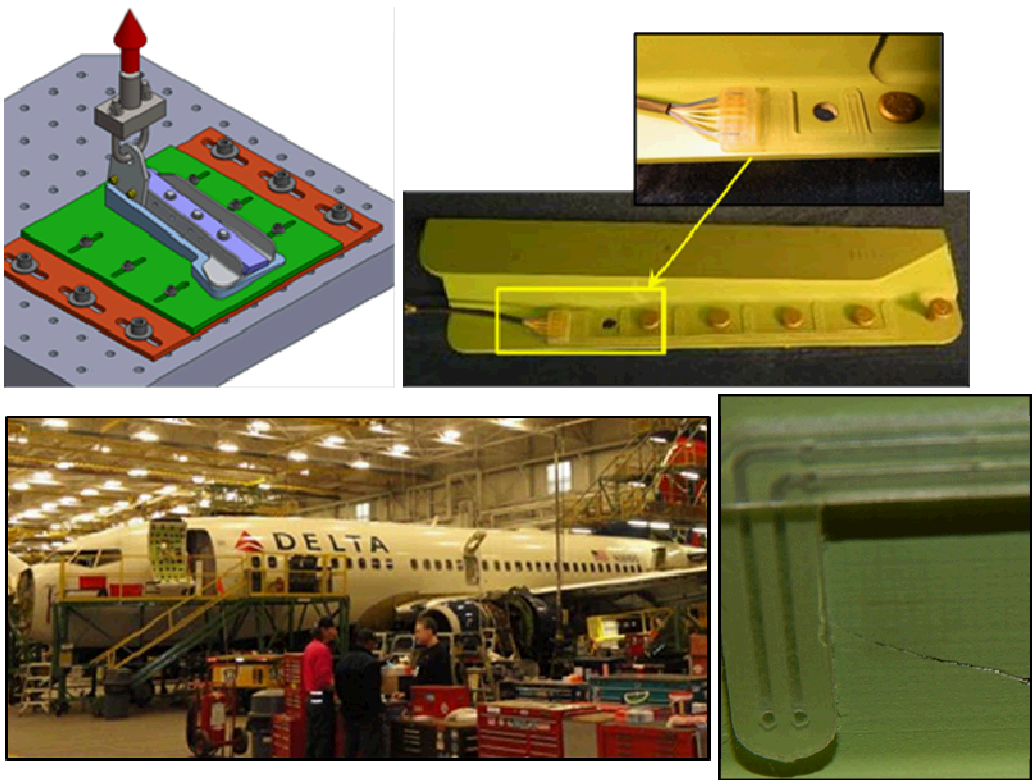

Figure 4: CVM Testing on Wing Box Fitting, Close-Up Showing Fatigue Crack Crossing into CVM Sensor and Installation of CVM Sensors on Delta Air Lines Aircraft for Flight Tests

SHM reliability calculations will depend greatly on the complexity of the structure and geometry of the flaw profile. Since it is based on a sample of the entire population (n data points), the confidence is less than 100%. Thus, the One Sided Tolerance Interval (OSTI) is greatly affected by two proportions: 1) the percent coverage which is the percent of the population that falls within the specified range (normally chosen as 90%), and 2) the degree of confidence desired (normally chosen as 95%). The data analyzed here consisted of fatigue cracks that were propagated in various metal specimens with the direction of growth aligned with the CVM mounted sensors. The data captured is that of the flaw length at the time for which the CVM provided sustainable detection. With these assumptions there exists a distribution on the flaw lengths at which detection is first made. In this context, the probability of detection for a given flaw length is just the proportion of the flaws that have a detectable length less than that given length. That is, the reliability analysis becomes one of characterizing the distribution of flaw lengths and the cumulative distribution function is analogous to a Probability of Detection (POD) curve. Assuming that the distribution of flaws is such that the logarithm of the lengths has a Gaussian distribution, it is possible to calculate a one sided tolerance bound for various percentile flaw sizes. To do this, it is necessary to find factors $K_{n,\gamma,\alpha}$ to determine the probability γ such that at least a proportion (1-α) of the distribution will be less than $X - K_{n,\gamma,\alpha}$ where X and S are estimators of the mean and the standard deviation computed from a random sample of size n. The data captured is the crack length at CVM detection. From the reliability analysis a cumulative distribution function is produced to provide the maximum likelihood estimation (POD). This stems from the one-sided tolerance bound for the flaw of interest using the equation:

$$T_{POD(90,\,95)} = X + (K_{n,\gamma,\alpha})(S) \qquad (1)$$

Where,

T = Tolerance interval for crack length corresponding to 90% POD with a 95% confidence
X = Mean of detection lengths
K = Probability factor (~ sample size and confidence level desired)
S = Standard deviation of detection lengths
n = Sample size
1-α = Detection level
γ = Confidence level

Because of physical, time or cost constraints, it is often impractical to inspect an entire population. Due to the limited number of data points, the reliability calculations induce a penalty by increasing the magnitude of the K (probability) factor. As the number of data points increases, the K value will decrease and the POD numbers could also decrease. The formula in equation (1) is set-up to produce the upper bound for the tolerance interval which represents the actual POD value. With the same parameters described above, the maximum likelihood estimate describing the optimal performance on the Probability of Detection for the OSTI approach can be calculated as:

$$\textbf{POD}(\text{Max Likelihood Est}) = \frac{1}{xS\sqrt{2\pi}} EXP\left(\frac{-(\ln(x) - X)^2}{2S^2}\right) \qquad (2)$$

As an example, the data acquired from CVM fatigue tests on 2.54” (0.1”) thick 2024-T3 aluminum structure were used to calculate the 90% POD level for CVM crack detection. This POD curve, representing the 95% confidence level, is plotted in Figure 5. The maximum likelihood estimated POD function, representing the optimum performance for CVM crack detection, was calculated from equation (2) and is plotted alongside the 95% confidence bound. The overall POD value (95%

confidence level) for CVM crack detection in 2.54 mm thick aluminum skin was determined to be 0.58 mm (0.023”). In this particular instance, it was desired to achieve crack detection before the crack reached 0.1” in length so this goal was achieved. In over 200 fatigue tests conducted using CVM sensors there were no false calls produced by the sensors.

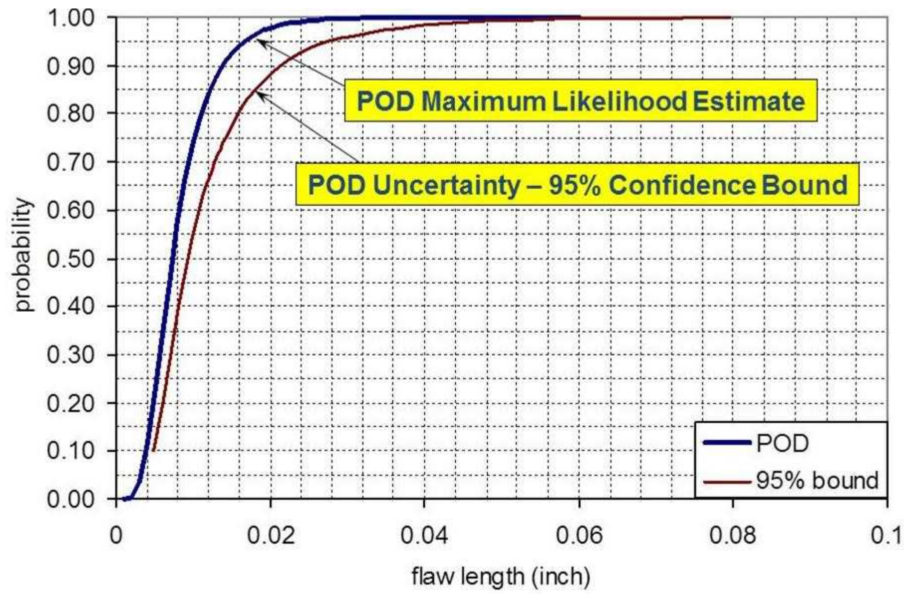

Figure 5: Probability of Crack Detection Curves Showing Detectable Flaw Lengths for CVM Sensor - Data Analysis Using One-Sided Tolerance Intervals

The results sited above are valuable for thin-walled structures such as those used in aircraft, automotive, and some pipeline construction. However, many civil structures use thick steel members. Earlier studies revealed that the thickness of the plate can affect CVM performance so additional performance tests studied CVM crack detection in thick-walled structures. Aircraft use thinner materials and have crack detection requirements of 1.27 mm to 2.54 mm in length. Civil structures contain thicker materials, have higher safety factors and can tolerate longer cracks such that their crack detection requirements are in the range of 12.7 mm to 25.4 mm in length. Additional tests studied CVM sensors monitoring cracks in 9.5mm thick steel. For the loaded structure, CVM crack detection occurred when the fatigue cracks ranged from 1.02 mm to 1.78 mm in length. For the unloaded condition, CVM crack detection occurred when the fatigue cracks ranged from 1.52 mm to 9.65 mm in length. However, regardless of whether the sensor monitoring is completed during a loaded or unloaded condition, the results indicate that CVM sensors could reliably detect fatigue cracks well before they reach 12.7 mm (0.5”) in length.

Multi-CVM Switch-Based System for Remote Bridge Monitoring

A real-time monitoring system was developed for remotely interrogating a distributed array of CVM sensors on a transportation bridge structure. It uses a series of pressure switches that can continuously monitor structures remotely via a wireless transmitting device. Sensors were placed in known fatigue critical locations on the bridge structure. When a crack breaches a sensor, the pressure switch is opened and, in turn, triggers a message that is sent to a central maintenance center. Up to 50 switches can be powered by one vacuum pump. The CVM monitoring system, shown in Figure 6, was mounted at a centralized point on the structure of interest. Sensors can be made in almost any shape and out of a material to suit the required environment. Multiple sensors can be arranged to monitor the growth of a crack. It may be that there is a known crack and a sensor placed ahead of the crack will be triggered if the crack grows. Often there are known critical locations at joints or welds that require monitoring. The CVM monitoring system can continuously update web sites or send automated text messages or e-mails so that operators can quickly and remotely ascertain the condition of a structure and determine if maintenance action is required. Solar cells were used to recharge the on-board batteries so that the system can provide continuous, real-time monitoring for 3-4 years without maintenance. Multiple years of field operation has revealed excellent bridge health monitoring capabilities of such an SHM system.

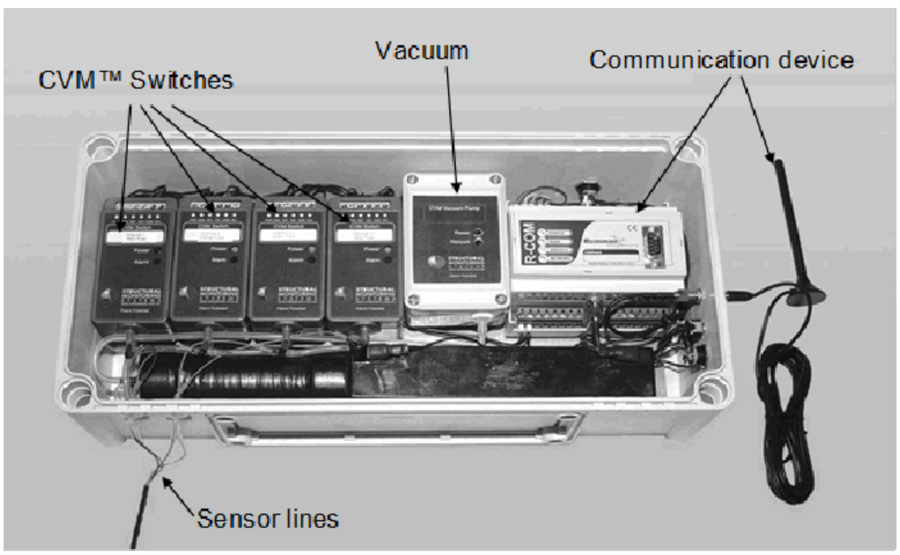

Figure 6: Real-Time, Remote Monitoring System for a Network of CVM Sensors

Conclusions

The effect of structural aging and the dangerous combination of fatigue and corrosion has produced a greater emphasis on the application of sophisticated health monitoring systems. Corrective repairs initiated by early detection of structural damage are more cost effective since they reduce the need for subsequent major repairs and may avert a structural failure. Through the use of in-situ CVM sensors, it is possible to quickly, routinely, and remotely monitor the integrity of a structure in service and detect incipient damage before catastrophic failures occur. These sensors can be attached to a structure in areas where crack growth is known to occur. On a pre-established monitoring interval, a reading can be taken remotely or from an easily accessible point on the structure. Each time a reading is taken, the system performs a self-test. This inherent fail-safe property ensures the sensor is attached to the structure and working properly prior to any data acquisition. In several structural categories studied, the CVM sensors provided crack detection well before the crack propagated to the critical length determined by damage tolerance analyses. In addition, there were no false calls experienced in over 200 fatigue crack detection tests. The sensitivity, reliability, and cost effectiveness of the CVM sensor system was demonstrated in both laboratory and field test environments.

Global SHM, achieved through the use of sensor networks, can be used to assess overall performance (or deviations from optimum performance) of large structures such as bridges, pipelines, transport vehicles, and buildings. The ease of monitoring an entire network of distributed sensors means that structural health assessments can occur more often, allowing operators to be even more vigilant with respect to damage onset.

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