

Real time crack detection using mountable comparative vacuum monitoring 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 disassembled and removed 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. A research program has been completed to develop and validate Comparative Vacuum Monitoring (CVM) Sensors for surface crack detection. Statistical methods using one-sided tolerance intervals were employed to derive Probability of Detection (POD) levels for a wide array of application scenarios. Multi-year field tests were also conducted to study the deployment and long-term operation of CVM sensors on aircraft. This paper presents the quantitative crack detection capabilities of the CVM sensor, its performance in actual flight environments, and the prospects for structural health monitoring applications on aircraft and other civil structures.

Keywords: Structural health monitoring (SHM); comparative vacuum monitorings; crack detection; probability of detection.

1. Introduction

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 approach thus optimizing maintenance labor. 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, overcome accessibility and depth of flaw impediments, and decrease maintenance costs by eliminating more time-consuming manual inspections.

Through the use of in-situ sensors, it is possible to quickly, routinely, and remotely monitor the integrity of a structure in service (Roach 2006). This requires the use of reliable structural health

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monitoring systems that can automatically process data, assess structural condition, and signal the need for human intervention. Prevention of unexpected flaw growth and structural failure can be improved if on-board health monitoring systems exist that could continuously assess structural integrity (Bartkowicz, *et al.* 1996, Beral and Speckman 2003, Roach 2004). SHM systems are able to detect incipient damage before catastrophic failures occur. 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.

2. Comparative vacuum monitoring

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. This paper focuses on the development, validation testing, and field installations of a mountable crack detection sensor and how it can be integrated into a health management system. The Comparative Vacuum Monitoring (CVM) sensor has been developed on the principle that a small volume maintained at a low vacuum is extremely sensitive to any ingress of air and is thus sensitive to any leakage (Roach, *et al.* 2006). Fig. 1 depicts a notional view of a CVM sensor network deployed on an aircraft to monitor critical sites over the entire structure.

Fig. 2 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



Fig. 1 Depiction of distributed network of sensors to monitor structural health

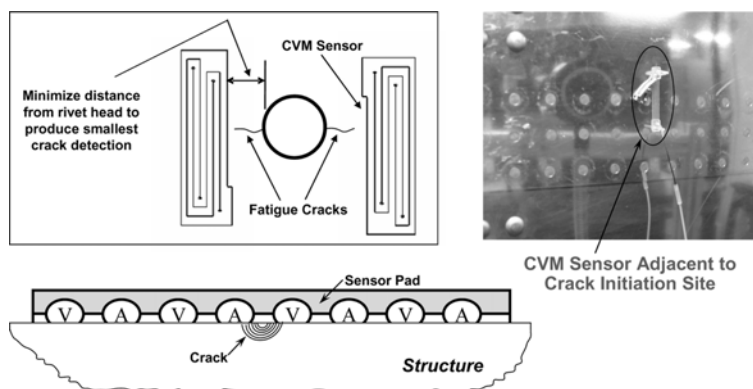


Fig. 2 Schematics depicting operation of CVM sensor and polymer sensor mounted on outer surface of a riveted lap joint

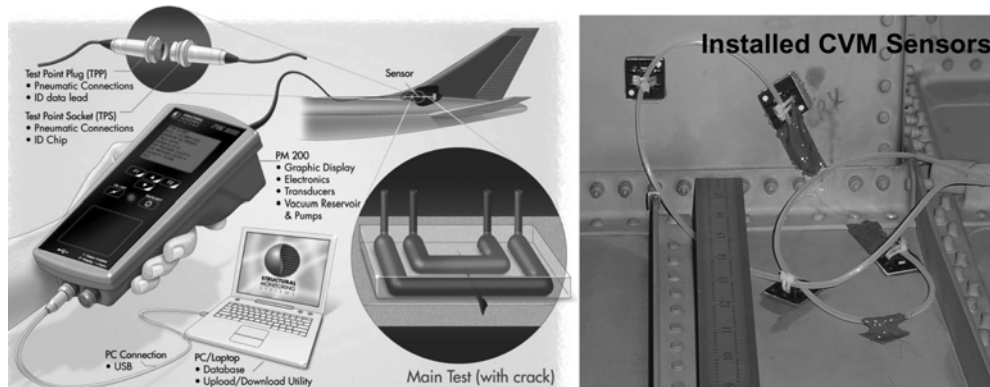


Fig. 3 Crack detection via CVM system and aircraft test installations of sensors

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 Fig. 3. Fig. 3 also shows sample CVM sensors mounted on an aircraft structure as part of a performance validation effort. It is important to note that the sensor detects surface breaking cracks once they interact with the vacuum galleries.

A series of 26 sensors have been mounted on structure in four different DC-9, B-757, and B-767 aircraft in the Northwest Airlines and Delta Air Lines fleets. Some of the sensors were installed over three years ago. Periodic testing demonstrated the successful, long-term operation of the CVM sensors in actual operating environments. This environmental durability study compliments the laboratory flaw detection testing described below as part of an overall CVM certification effort.

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. 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.

3. Applications for crack detection using CVM sensors

Recent events have demonstrated the need to address critical infrastructure surety needs (U.S. White House document 2003). 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 (see Figs. 4 and 5). These key assets represent a broad array of unique facilities, sites, and structures whose disruption could have significant consequences (Schwendeman and Hedgren 2003, U.S. Army Engineering Manual 2001). Damage can arise from service loads as well as from external impact or other off-design conditions.

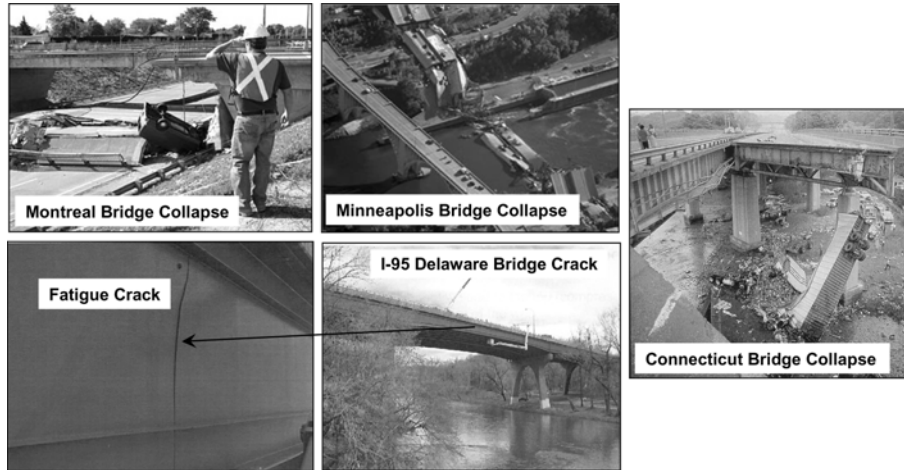


Fig. 4 Bridge applications for in-situ structural health monitoring technology



Fig. 5 Applications for in-situ crack detection using CVM sensors

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. For steel structures, corrosion flaws reduce the cross section of members and the effect of repeated loading can generate fatigue cracks. Budget restrictions can limit inspections or repairs such that only the more serious problems are addressed. 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. Fig. 4 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.

4. CVM performance on thin aluminum structures

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 (Roach, *et al.* 2006, Wheatley, *et al.* 2003). Fatigue tests were completed on simulated aircraft panels to grow cracks in riveted specimens (see Fig. 6) 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. In order to properly consider the effects of crack closure in an unloaded condition (i.e. during sensor monitoring), a crack was deemed to be detected when a permanent alarm was produced and the CVM sensor did not maintain a vacuum even if the fatigue stress was reduced to zero.

This test program produced a statistically-relevant set of crack detection levels for 1.02 mm, 1.78 mm, and 2.54 mm thick panels in both the bare and primed configurations. Fig. 6 shows the fatigue test set-up used to grow cracks and a close-up photo of the CVM sensors monitoring cracks initiating from a center hole. Fig. 7 shows a photo of a fatigue crack as it engages the first vacuum gallery of a CVM sensor. The pressure rise, corresponding to a rupture in the gallery and a leakage path to atmospheric pressure, is shown on the right side of Fig. 7. The large increase in the pressure corresponds to crack detection. One signal (lower curve) corresponds to vacuum levels produced when there is no crack indication and the other signal (upper curve) occurs when a vacuum is not achievable. This latter signal is produced when the CVM detects a crack.

Table 1 summarizes some of the crack detection results for the 2.54 mm thick panels. Crack detection lengths ranged from 0.18 mm to 0.48 mm in length. Fatigue tests have shown that pressure levels in



Fig. 6 CVM sensors monitoring crack growth on aluminum test specimens

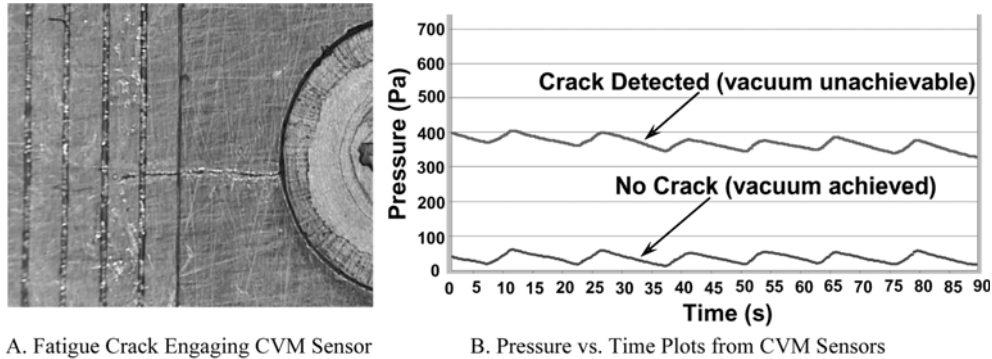


Fig. 7. Fatigue crack crossing into CVM galleries and pressure response used to indicate the presence of a crack

Table 1 CVM crack detection values from 2.54 mm thick aluminum plate (2024-T3)

CVM crack detection on 2.54 mm thick aluminum plate							
Panel	Fastener crack site	Number of fatigue cycles	Crack length at CVM detection (growth after install in mm)	PM-4 read-out (Pasm)	PM-4 indicate crack (Y or N)	90% POD level	False calls
1	1-L	3505	0.178	2123	Y	0.584 mm	0
1	1-R	3205	0.178	1938	Y		
1	2-L	5350	0.254	2251	Y		
1	2-R	5550	0.279	1954	Y		
1	3-L	6650	0.229	4526	Y		
1	3-R	7099	0.406	7099	Y		
2	1-L	3100	0.279	1786	Y		
2	1-R	3400	0.356	1707	Y		
2	2-L	5300	0.127	2383	Y		
2	2-R	5300	0.406	2204	Y		
3	1-L	4475	0.483	1790	Y		
3	1-R	4825	0.330	1904	Y		
3	2-L	7025	0.203	2100	Y		
3	2-R	7878	0.254	4302	Y		

excess of 300 Pa were measured during fatigue testing, however, the compressive residual stresses at the tip of a fatigue crack could allow a vacuum to be produced when the specimen was unloaded. The numbers presented in Table 1 correspond to permanent alarm levels for cracks engaging CVM sensors and the structure in an unloaded condition.

5. CVM validation - data analysis using one-sided tolerance intervals

The CVM sensor is based on the principle that a steady-state vacuum, maintained within a small volume, is sensitive to any leakage. A crack in the material beneath the sensor will allow leakage resulting in detection. The data analyzed here consist 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 $(1-\alpha)$ 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:

$$\text{Crack Length for 90\% POD}_{(95\% \text{ Confidence})} = X + (K_{n,0.95,\alpha})(S) \tag{1}$$

Where,

- 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

The 90% POD level for crack detection on 2.54 mm thick aluminum, calculated from Eq. (1), is also listed in Table 1. Due to the limited number of data points, the reliability calculations induce a penalty by increasing the magnitude of the K (probability) factor. As a result, the overall POD value (95% confidence level) for CVM crack detection in 2.54 mm thick aluminum skin is 0.58 mm. This POD curve is plotted in Fig. 8. As the number of data points increases, the K value will decrease and the POD numbers could also decrease. In this particular instance, it was desired to achieve crack detection before the crack reached 2.54 mm in length so this goal was achieved. Table 2 summarizes the 90%

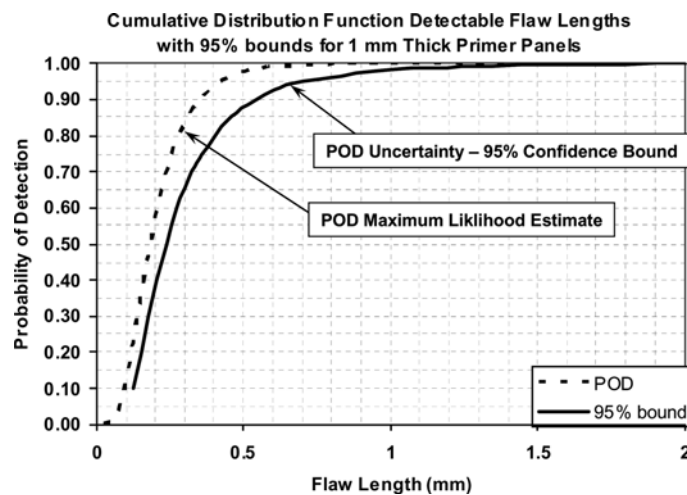


Fig. 8. Typical probability of crack detection curves generated by CVM data and data analysis using one-sided tolerance intervals

Table 2 Summary of crack POD levels for CVM deployed on different materials, surface coatings, and plate thicknesses

Material	Plate thickness (mm)	Coating	90% POD for crack detection (mm)
2024-T3	1.02	Bare	1.24
2024-T3	1.02	Primer	0.53
2024-T3	1.80	Primer	1.07
2024-T3	2.54	Bare	6.91
2024-T3	2.54	Primer	2.29
7075-T6	1.02	Primer	0.66
7075-T6	1.8	Primer	0.84
7075-T6	2.54	Primer	0.58

POD levels (95% confidence level) for CVM crack detection for the array of thin-walled aluminum plates tested. Note that there were no false calls produced by the CVM sensors in any of the tests.

6. CVM performance on thick steel structures

The results cited 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 a second round of tests looked at CVM crack detection in thick-walled structures. It should be noted that aircraft use thinner materials and have crack detection requirements of 1.27 mm to 2.54 mm in length. Civil structures contain thicker materials and have higher safety factors. Thus, these structures can tolerate longer cracks and their crack detection requirements are in the range of 12.7 mm to 25.4 mm in length. CVM sensors can be fabricated with different gallery sizes in order to accommodate various sensitivity requirements. Fig. 9 shows the installation of a CVM sensor on a 9.5mm thick steel (ASTM 572) plate. The seeded fatigue crack along the edge of the specimen is visible. These test specimens were then exposed to tension-tension fatigue tests in order to propagate the crack into the CVM sensor. Figs. 9 and 10 show the overall test set-up along with the equipment used to monitor the CVM sensors.

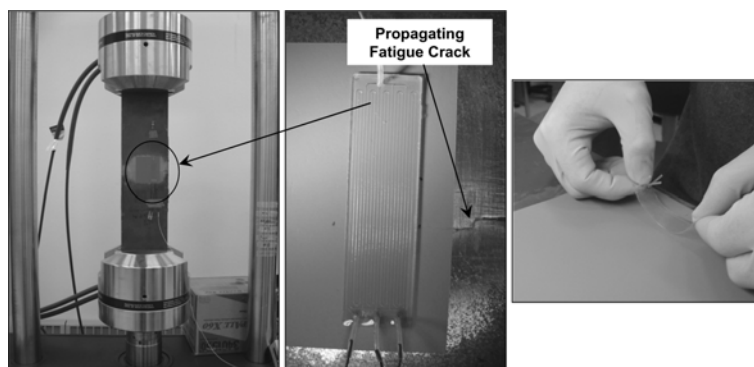


Fig. 9. Installation of CVM sensor on primed steel surface, fatigue test of steel specimens, and close-up of fatigue crack approaching sensor

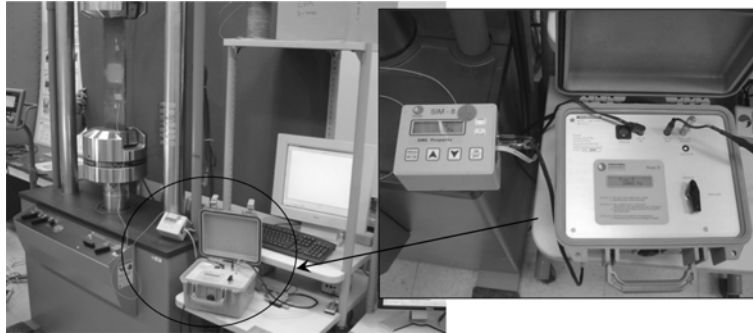


Fig. 10 Overall set-up for monitoring crack growth with CVM sensor system and close-up of laboratory sensor interrogation equipment

Table 3 Crack detection produced by CVM sensors on 12.7 mm thick steel plate

Test specimen	CVM set-up Sensor	CVM set-up			CVM crack detection with no load			
		Initial crack length (mm)	Initial sensor location [distance from specimen edge] (mm)	Baseline CVM pressure reading [no crack engagement condition] (Pa)	Cycles at initial CVM crack detection [under load]	CVM pressure reading at crack detection [under load] (Pa)	Total crack length at initial CVM crack detection [under load] (mm)	Crack growth for CVM crack detection [engagement with CVM sensor](mm)
SYN FAT 24	1	27.94	27.94	1,580	2,137	16,500	29.21	1.270
SYN FAT 24	2	37.59	38.61	1,435	9,451	19,600	39.88	1.270
SYN FAT 24	3	48.26	48.77	1,460	10,698	12,250	50.55	1.778
SYN FAT 19	4	29.72	30.99	1,488	115,000	11,610	32.64	1.651
SYN FAT 19	5	39.37	41.40	1,500	139,843	17,000	42.67	1.270
SYN FAT 19	6	45.85	47.50	1,500	145,800	19,000	48.64	1.143
SYN FAT 22	7	23.88	29.21	1,740	150,839	7,000	30.48	1.270
SYN FAT 22	8	37.59	38.86	1,363	184,412	17,800	40.39	1.524
SYN FAT 22	9	43.18	44.58	1,530	191,315	17,000	45.72	1.143
SYN FAT 21	10	25.40	27.56	1,510	44,800	3,000	29.08	1.524
SYN FAT 21	11	37.97	38.86	1,433	88,100	19,000	40.64	1.778
SYN FAT 23	12	36.83	38.10	1,457	2,000	11,000	39.62	1.524
SYN FAT 23	13	45.97	46.74	1,570	6,400	20,000	47.75	1.016

Compressive stresses around the tip of a fatigue crack create a tight tip when the load is removed. As a result, the initial engagement of a crack with a CVM sensor may induce a high pressure reading (crack detection) when the structure is under load; however, the compressive residual stresses at the tip of a fatigue crack could allow a vacuum to be produced when the specimen is unloaded. Therefore, crack detection can be achieved much earlier if the sensors can be monitored while the structure is in use. In the case of real-time monitoring for the steel plate test series, CVM crack detection results for the loaded steel structure are summarized in Table 3.

For the loaded structure, CVM crack detection occurred when the fatigue cracks ranged from 1.02 mm to 1.78 mm in length as summarized in Table 3. This would correspond to the ability of the CVM sensor to monitor cracks in real-time while the structure is in use. 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

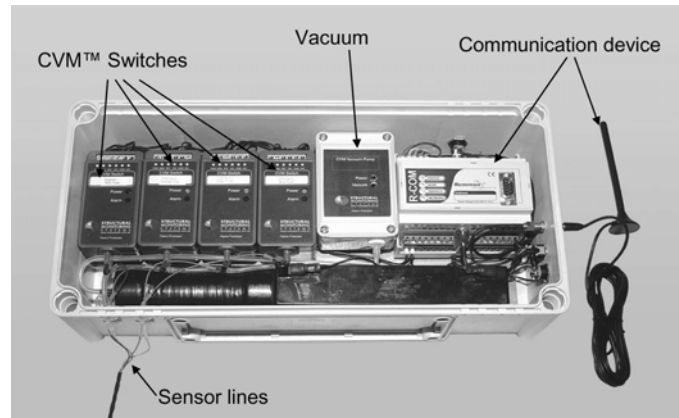


Fig. 11 Real-time, remote monitoring system for a network of CVM sensors

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 in length.

7. Multi-CVM switch-based system for remote bridge monitoring

A real-time monitoring system has been developed for remotely interrogating a distributed array of CVM sensors. It uses a series of pressure switches that can continuously monitor structures remotely via a wireless transmitting device. Sensors are placed in known fatigue critical locations on a structure such as a bridge, pipeline, or factory assembly. 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 Fig. 11, is mounted at a centralized point on or near 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.

8. Deployment of health monitoring sensor networks

Distributed sensor networks can be deployed in any of the three approaches listed below. These options are listed in the order of increasing complexity, however, less labor is required to monitor the systems as they become more sophisticated.

1. In-situ sensors only – The sensors are the only items permanently installed on the structure. At the desired inspection intervals, power, signal conditioning, and data acquisition electronics are manually transported to the structure to be monitored. The sensors are linked to the monitoring electronics via a connector and flaw detection is completed by an inspector at the site.

2. Sensor network with in-situ data acquisition – In this system, miniature, packaged electronics are also placed in-situ with the sensor network. The electronics contains the necessary power, memory and programmable circuitry for automated data logging. The data is periodically downloaded to a laptop through manual hook-ups at the site.

3. Sensor network with real-time data transmission to a remote site – This approach is similar to item #2 with the addition of a telemetry system that allows for continuous, wireless transmission of data to a web site. The web site can be programmed to interrogate critical aspects of the data and use pre-set thresholds to provide continuous green light/red light information regarding the health of the structure. The web site can even be programmed to automatically send an e-mail to operation personnel if the condition monitoring process indicates the need for repairs or other maintenance.

The latter approach allows for true condition-based maintenance in lieu of maintenance checks based on time of operation. A series of expected maintenance functions will already be defined, however, they will only be carried out as their need is established by the health monitoring system. The use of condition-based maintenance coupled with continuous on-line structural integrity monitoring could significantly reduce the cost of inspection, maintenance, and repair.

9. Conclusions

The effect of structural aging and the dangerous combination of fatigue and corrosion, coupled with recent failures in civil structures, has produced a greater emphasis on the application of sophisticated health monitoring systems. In addition, the costs associated with the increasing maintenance and surveillance needs of aging structures are rising. 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.

Comparative Vacuum Monitoring is a simple pneumatic-based sensor technology developed to monitor the onset and growth of structural cracking. This is an important part of Structural Health Monitoring. 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. In several structural categories studied, the CVM sensors provided crack detection well before the crack propagated to the critical length determined by damage tolerance analysis. In addition, there were no false calls experienced in over 150 fatigue crack detection tests. The sensitivity, reliability, and cost effectiveness of the CVM sensor system was demonstrated in both laboratory and field test environments.

Together with acoustic, vibration, and corrosion sensors, CVM can form a suite of sensor types that will enable the state of a structure to be rapidly assessed in real-time. Furthermore, implementation costs can be minimized through common power and communications packages for groups of sensor types. 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, large 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 flaw onset.

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