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Corrosion and Fatigue Monitoring Sensor Networks

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ABSTRACT

This paper describes networks of electromagnetic sensors for fatigue and corrosion monitoring of aircraft, spacecraft, rotorcraft, ships and other high value assets. Inductive (MWM®) and capacitive (IDED®) sensors are described for the detection and monitoring of hidden (buried) corrosion and fatigue damage (including buried cracks). Some air and space vehicles experience corrosion and fatigue damage over wide areas and in numerous, i.e., multiple, sites; for others, just a handful of fatigue critical locations become the life limiting factors. This paper addresses the latter case where a limited number of permanently mounted sensors can substantially impact total ownership costs for these high value assets. Such life limiting locations are often in areas with limited access or at surfaces buried between layers, so that conventional inspections cannot be readily performed. These sensors can be mounted on an exposed surface or embedded between layers to enable monitoring of these areas. The sensor's electrical leads are routed to easily accessible locations to permit scheduled or unscheduled inspections without disassembly. To be practical such sensors must be durable and light-weight; but most importantly they must be reliable over the remaining life of the vehicle.

INTRODUCTION

This paper describes advances in corrosion and fatigue monitoring sensor network development using MWM and IDED sensors and sensor arrays. The corrosion monitoring technology described here is relatively new and requires significant research before field implementation, while the MWM-Array fatigue monitoring technology is in use in numerous laboratories as a commercial product to support coupon and component fatigue testing and is being transitioned to the fleet for specific applications.

For corrosion damage protection, a variety of approaches such as the use of sealants and corrosion protection coatings (CPCs) are used to protect critical metal components from the corrosive environment. On new platforms with composite-metal joints, galvanic corrosion is a particular concern. Maintenance and repair of affected components are generally far more expensive if damage is not detected early. Historically, Nondestructive Evaluation (NDE) in the depot has focused on relatively wide area corrosion problems, e.g., KC-135 lap joints. The focus for such legacy platforms is typically detection of damage early enough to permit a limited repair; also, relatively extensive damage can be tolerated on some of these platforms. Moving such inspections from the depot to the field would reduce the logistics footprint and support early scheduling of repairs for military aircraft. Embedded sensing is one method that can enable field inspections for corrosion in difficult-to-access locations. The wide area nature of corrosion damage, has limited the practical applications of on-board sensors for corrosion. Environmental sensors had received substantial attention as a means for addressing this issue; however, environmental monitoring alone has proven limited as well, since an aggressive environment with a sound corrosion protection system will not result in corrosion. This paper introduces a new approach that uses a combination of IDED and MWM sensors embedded in critical joints. The goal is not only to detect metal loss, as with eddy current based NDE methods for corrosion, but also to detect corrosion products and moisture ingress within the joint itself.

For fatigue damage, critical locations are often better defined, especially for legacy aircraft. For example, on some rotorcraft and fighter aircraft, fewer than 20 fatigue critical locations may define the remaining life limits. For these locations it is often possible, if cracks are detected early enough, to splice in a repair section or add a doubler to enable the vehicle to remain in service. Early detection of damage at such locations is the critical driver to cost reduction.

This paper describes two types of quasistatic sensors and implementation of these sensors in fatigue and corrosion monitoring sensor networks. The MWM (Meandering Winding Magnetometer – developed by Goldfine and Melcher at MIT in the 1980s) and the segmented-field IDED (a multiple spatial wavelength Interdigitated Dielectrometer – developed at JENTEK Sensors in the 1990s based on earlier work by Melcher at MIT). The MWM is an inductive, eddy current, sensor and the IDED is a capacitive sensor [1-6]. MWMs are suitable for metals, graphite fiber composites, reinforced carbon carbon composites, and low observable coatings (nonconducting, magnetizable coatings using magnetic particle suspensions), while the IDED is suitable for characterization of glass fiber composites, corrosion protection coatings, sealants, glass, paint, and wood, as well as for detection/monitoring of corrosion products, moisture ingress and monitoring of cure states of epoxies and adhesives.

QUASISTATIC SENSING

Surface mounted or embedded electromagnetic sensors operating in the relatively low frequency, quasistatic regime are well suited to monitoring damage in structures and engines. In the quasistatic regime, the sensing fields are predominantly either magnetic or electric. In both JENTEK's inductive and capacitive sensors, a single drive element is used with multiple sense elements to facilitate parallel data acquisition of sensor responses and to eliminate cross-talk or interference between multiple sense elements. For these sensors, the responses can be modeled accurately. This allows calibration information to be reused each time electrical contact to the sensor is established prior to performing a measurement. The robustness of these sensing modalities is also advantageous for leave-in-place sensors, where it is important to be able to perform self-diagnostics on the sensor to confirm correct sensor operation.

Magnetoquasistatic Sensing

Magnetoquasistatic or inductive sensing uses magnetic fields to monitor changes in the properties of magnetic and/or conducting materials such as metals [1-4, 6]. Example geometries for MWMs are shown in Figure 1. Electrical current is passed through one or more drive winding loops to impose a near-surface magnetic field in the test material. Secondary windings located between the drive winding segments are used to sense the perturbations in the magnetic field due to the presence and condition of the test material. Connections are made to individual sense elements so that higher spatial resolution can be obtained. For example, the array of Figure 1 (left) can be scanned over a test material in a direction perpendicular to the row of sense elements to produce a 2-D image or the sensor can be permanently mounted to provide monitoring of several inches of material for hidden corrosion or fatigue damage.

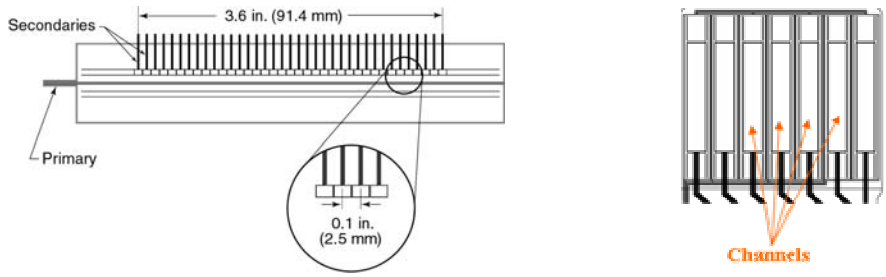


Figure 1. Representative MWM-Arrays; (left) 37 channel FA24. (right) 7 channel FA47.

The most significant advantage of the MWM-Arrays are that they perform inspections in essentially the same manner as a conventional eddy current sensor, by inducing eddy currents at multiple frequencies; but, they use precomputed databases to provide robust and reliable calibration and measurement performance. Multiple frequencies enable detection of not only near surface fatigue damage (cracks), but at lower frequencies, enable projection of magnetic fields deeper into the surface (e.g., up to 0.25 in. or in some cases as deep as 0.5 in.) to detect buried cracks and hidden damage. Furthermore, one of the most critical needs of an embedded sensor is self diagnostics. MWM-Arrays monitor the actual electrical conductivity of the material under test. Thus, the sensor is calibrated and diagnosed by monitoring the temperature of the material and correlating the temperature with the MWM conductivity measurements. This enables practical recalibration of MWM sensors in-place [6].

Electroquasistatic Sensing

Electroquasistatic or capacitive sensing uses electric fields to monitor changes in the properties of insulating or weakly conducting dielectric materials, such as composites, sealants, and CPCs. The basic structure for a single-sided IDED capacitive sensor is shown in Figure 2. One set of electrode fingers are driven by a sinusoidal, time varying signal with known amplitude, while the second set of interdigitated fingers is virtually grounded. The terminal current constitutes the sensed signal. For layered or non-homogenous materials, such as composites, in which dielectric properties vary with depth, the measured transadmittance between the drive and the sense electrode is a thickness and depth-weighted function of the dielectric properties (effective complex permittivity) of the various regions.

The periodic variation of electric potential along the surface produces an exponentially decaying electric field that penetrates into the medium. The small wavelength sensors (i.e., with small electrode spacing) will primarily respond to changes of material properties near the sensor-material interface, while larger wavelength sensors (with wider electrode spacing) respond to changes farther from the sensor interface. Thus, multiple wavelength sensors can be used to measure spatial profiles of dielectric properties, as a function of depth [5,6]. To ensure that each spatial wavelength is responding to the same test material region, multiple sense elements have been integrated into a single sensing structure to form a co-located sensor array as shown in Figure 2 [6]. These IDED designs enable many new applications, including health monitoring of glass fiber composites and embedding in joints for monitoring of corrosion damage, moisture ingress, corrosion protection system condition, and even curing of adhesives and epoxies during manufacturing and repair.

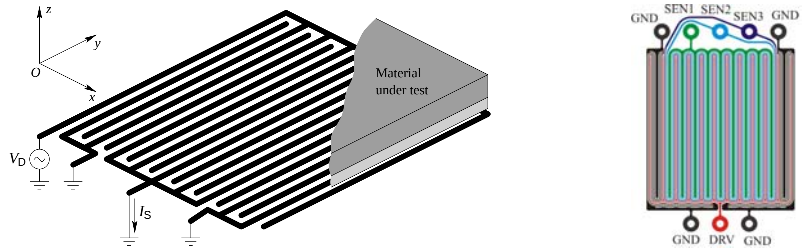


Figure 2: (Left) IDED sensor in contact with a test material. (Right) Schematic diagram for a three-wavelength co-located interdigitated electrode sensor.

Grid Measurement Methods

The quasistatic sensor response is converted into material or geometric properties using a Measurement Grid. These grids enable the conversion of the sensor response (transadmittance or transimpedance between drive and sense elements) into property estimates for two unknown properties of interest [1-6]. These grids are two-dimensional pre-computed databases of sensor responses that are used to calibrate and perform measurements of absolute materials properties. Typically, grids relate two measured parameters to two unknowns, such as the dielectric constant and lift-off, electrical conductivity and lift-off, or metallic coating thickness and lift-off. For solution of three or more unknown problems, higher order databases are used. The precomputed database methods also enable real time data processing both on-board for continuous monitoring and by plugging in to on-board sensors using portable data acquisition and processing.

EXAMPLE APPLICATIONS

Embedded MWM-Arrays for fatigue monitoring

Networks of sensor arrays have been used to monitor damage initiation and propagation in metallic structures using MWM-Arrays. Figure 7 (left) illustrates a four-hole joint specimen representative of an aircraft structural joint, with embedded MWM-Arrays. The specimen was cycled in a load frame to induce fatigue cracking at the fastener holes. The MWM-Arrays successfully detected and monitored crack progression throughout the test and remained functional even after the specimen failed. Figure 7 (right) shows a ten-hole specimen that was also monitored with embedded MWM-Arrays. The MWM-Arrays were mounted between the holes in the lower and upper rows. Both the test row, which included precracks, and the non-test row were monitored using two instruments operated by a single laptop computer.

The MWM-Array technology for fatigue monitoring has been described in numerous recent presentations and papers. This includes sensors for monitoring the internal surface of open holes in fatigue test coupons to detect cracks below 100 μm in length (0.004 in.) and to monitor their growth, new strain-life coupon sensors to determine the number of cycles to a pre-specified flaw size (e.g., 0.01 in. depth) as required in some testing scenarios, as well as numerous tests with embedded sensors.

More recent demonstrations have also included damage monitoring for graphite fiber composites using MWM-Arrays. These tests have demonstrated capability to detect buried damage (e.g., delaminations/disbonds/fiber damage detection through a 0.25 in. skin) in composite-composite joints, as well as to monitor local strain, using projected field MWM-Arrays. These arrays monitor bulk fiber conductivity changes, using relatively large area sensors mounted at accessible surfaces [6].

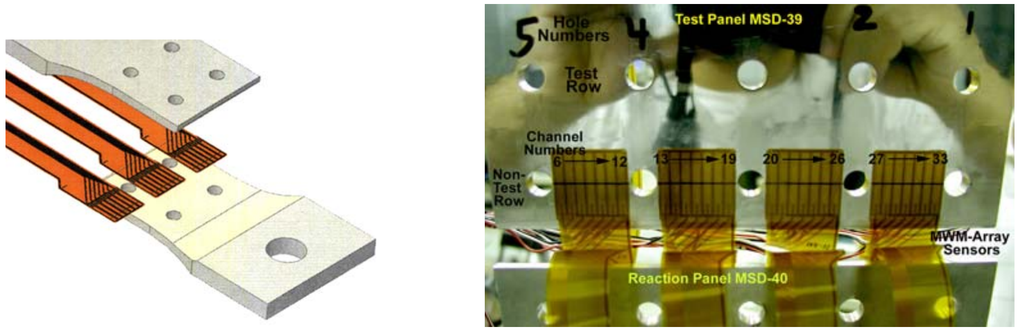


Figure 7: (Left) Schematic for MWM-Arrays mounted along a row of fastener holes in a four-hole specimen. (Right) A ten-hole specimen with embedded MWM-Arrays shown prior to joint assembly.

Simulated hidden corrosion imaging

Measurements were performed on a test panel containing areas of simulated hidden corrosion. The panel was fabricated from two sheets of 7075-T6 aluminum alloy, each 0.040 in. thick. The sheets were joined by six rows of thirteen removable fasteners. There were five rows of flat bottom holes located between the fastener rows. The flat bottom holes range from 0.125 to 1.0 in. in diameter and from 0.0008 to 0.008 in. in depth, and are located on the bottom sheet at the interface between the sheets. Figure 3 provides a drawing of a section of the panel. In this case, scans were made using an existing FA24 (37 channel) sensor, JENTEK impedance instrument, and GridStation inversion system. An MWM-Array image obtained by scanning of the row of 0.008 in. deep, flat bottom holes is shown in Figure 4. The color scale represents remaining total thickness of material, which agrees well with the known values for the higher volume areas. Since the fasteners had raised heads, only the response of the sense elements positioned between the fasteners is shown. Similar results were obtained for the other rows.

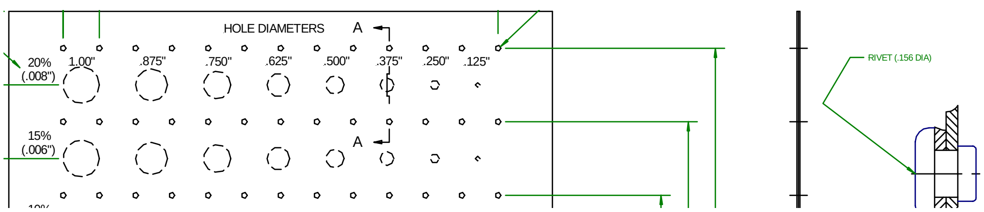


Figure 3. The test panel contains five rows of flat bottom holes located between the six rows of fasteners. The clear space between the fastener heads or washers is approximately 0.75 inches.

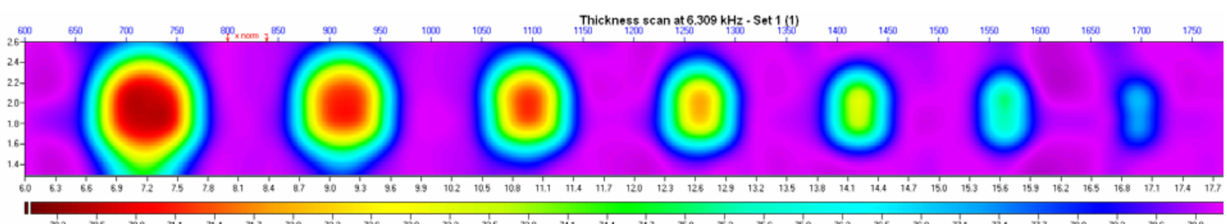


Figure 4. MWM-Array preliminary results for the row of 0.008 in. deep (10% thickness loss) flat bottom holes at the hidden interface between the two plates.

Hidden metal loss monitoring using a permanently mounted MWM-Array

The capability of an embedded MWM to monitor material loss inside a lap joint or on the far side of a metallic aircraft skin was demonstrated as shown in Figure 5. Here, three 0.040 in. aluminum 2024 layers were stacked and clamped together with a 0.002 in. polyester shim placed between two of the skins to provide a nominal initial gap. An FA24 MWM-Array was mounted on the surface of the top skin. The middle skin was comprised of separate sheets to enable a portion of the layer to be removed, gradually, to simulate metal loss at the center of the stack-up. The sliding section was slowly removed. Subsequent measurements show the spatial progression of the air gap between the skins. The response to this progressive material loss is shown in Figure 6. The measured properties displayed here are the sensor lift-off and the internal air gap height. The initial vertical air gap value of approximately 0.002 in. (shown in red) is consistent with the presence of the polyester shim. The lift-off is the distance between the sensor and the top aircraft skin and remains relatively constant.

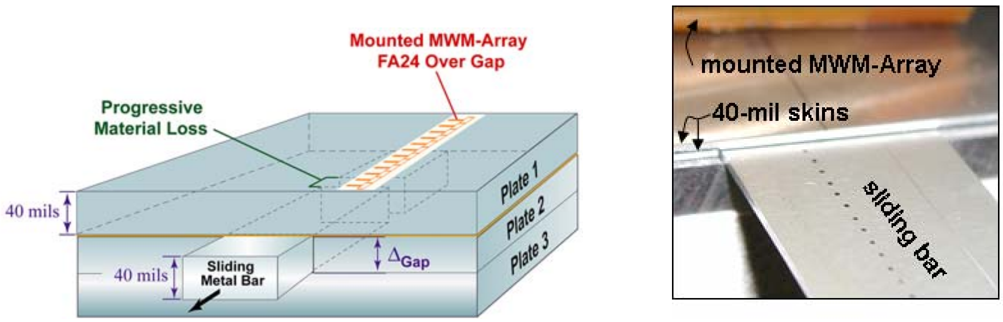


Figure 5. Progressive metal loss multilayered construct drawing and photograph.

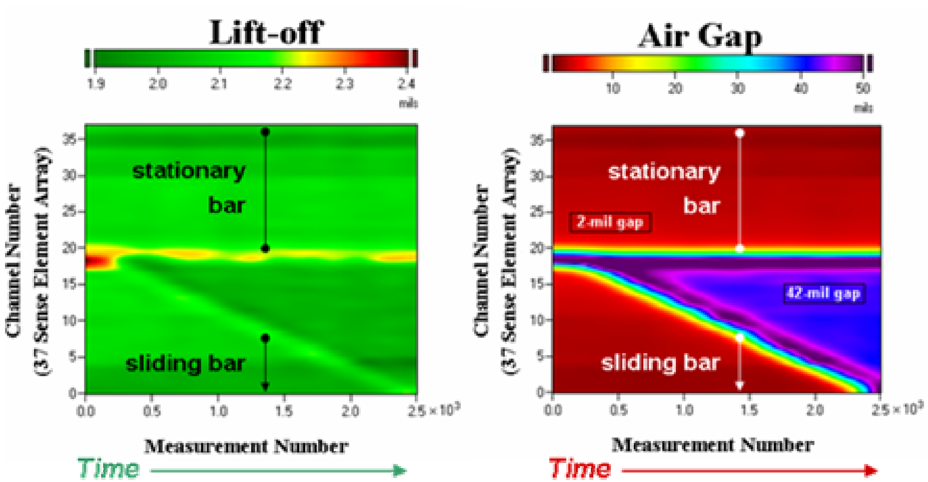


Figure 6. Mounted FA24 array data images showing progressive material loss.

Embedded IDED monitoring

To illustrate the use of an embedded sensor in a joint, a permanently mounted IDED sensor was used to monitor the cure state of a sealant and to detect moisture ingress at the bondline in a laboratory demonstration. The experimental set-up is shown in Figure 9. The outer layer was a two-part, epoxy cured polythioether compound used for aircraft fuel tanks and structures. Below the sealant is a 0.005 in. thick micro-porous layer sandwiched between two 0.0005 in. thick plastic sheets. The end of the porous layer extends well beyond the sensor in order to act as a channel for the introduction of moisture. Immediately below the plastic film, the segmented field IDED sensor was mounted on a 0.250 in. aluminum alloy plate.

After calibration in air using a model-based method, the sensor response was monitored using a 3-unknown Grid Method for three days from the initial application of the sealant through multiple wetting and drying cycles. During this time, the effective sealant permittivity, sealant conductivity and sensor lift-off were measured at intervals of 150 seconds. Figure 10 (left) shows the sealant property measurements for the first 30 hours following application of the sealant. Once the sealant cure was complete, water droplets were applied to the portion of the porous layer that extended beyond the sealant. Figure 10 (right) shows the permittivity response to the wetting and drying processes. While the introduction of the water was an abrupt event, the sensor response during the drying process better indicates the high sensitivity of this sensing modality to smaller changes in moisture content. This ability to sense minute quantities of moisture was subsequently displayed a second time by a rise and fall in permittivity corresponding with a passing rainstorm.

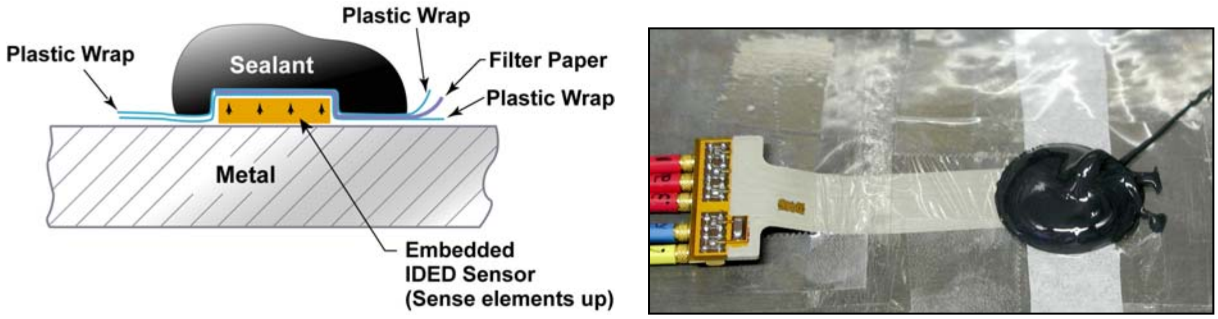


Figure 9: An embedded sealant construct used for cure monitoring and simulated water intrusion.

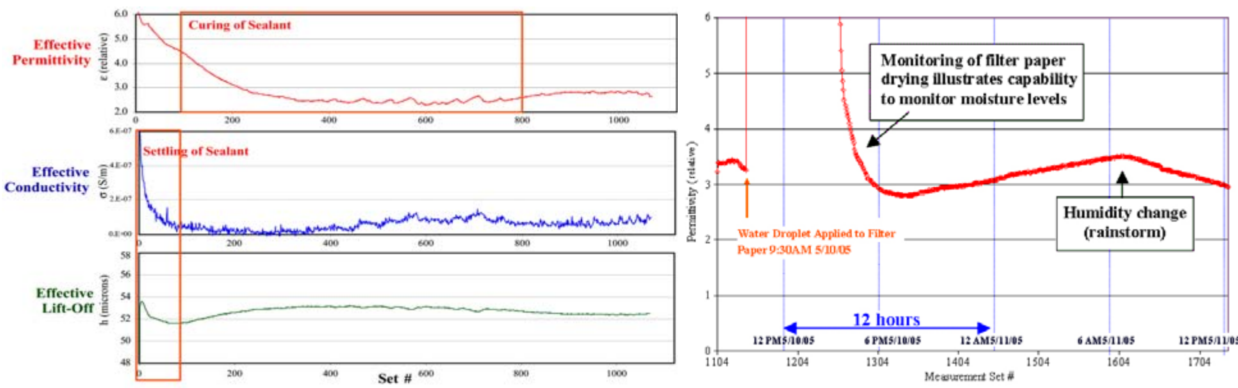
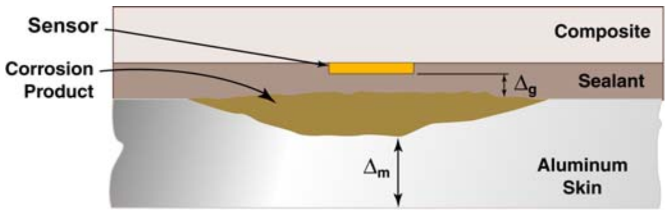


Figure 10: (left) In-situ sealant cure monitoring. (right) Sealant permittivity during water exposure.

Embedded IDED corrosion product monitoring

Also, computer simulations have demonstrated that an embedded IDED sensor can detect the changes in average dielectric response associated with the growth of corrosion products. Changes in the complex permittivity produced by conversion of metal to either an oxide or hydrolyzed layer at the interface between the composite or sealant and the metal substrate were simulated to illustrate the feasibility of corrosion product detection and monitoring. In the simulation, intended to evaluate the sensitivity of the multiple wavelength dielectric sensors to the presence of corrosion products, an IDED sensor was assumed to be near an aluminum surface, with a stand-off distance of 0.002 or 0.010 in. Figure 11 (left) illustrates the physical arrangement that was simulated. It was assumed that corrosion on the surface of the aluminum led to the formation of corrosion products. These products are typically aluminum oxide or aluminum hydroxide. The corrosion products were taken as a uniform dielectric layer that is electrically insulating. Figure 11 (right) shows the SNR value using the short and middle spatial wavelength electrodes. The SNR value increases as the corrosion product layer increases in thickness. It increases slightly faster for lower values of dielectric constant of the corrosion product layer.



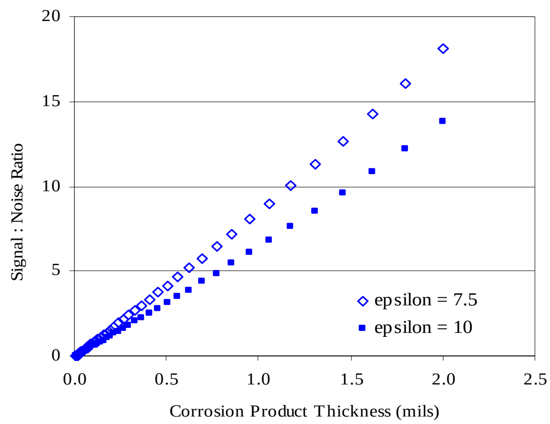


Figure 11. (left) Illustration of a sensor embedded within a composite-metal joint. (right) Corrosion product layers producing signal to noise ratios (SNRs) greater than one should be detectable.

SUMMARY

MWMs and IDEDs are thin, flexible, lightweight and extremely reliable. These properties make them ideal for surface mounting and embedding to provide in-situ monitoring capabilities. This includes the assessment of corrosion and fatigue damage as well as monitoring of sealant and protective coatings. Demonstrations have been performed on coupons, components and full scale test articles. On-going work is aimed at transitioning this technology to on-aircraft, rotorcraft, and ship-board applications. By combining IDED and MWM sensors into hybrid constructs, their complementary capabilities can be further exploited. For example, in corrosion monitoring, the MWM can provide metal loss monitoring while the IDED can provide moisture ingress and corrosion product detection. Hybrid MWM/IDED sensors having both modes within the same sensor footprint have been conceived [1-6].

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