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Detecting stress and fatigue cracks

Finding and characterizing surface breaks using open-ended rectangular waveguides

Metal fatigue or failure usually begins from the surface. Aircraft fuselage, turbine blades and nuclear power plant steam generator tubings are examples of where this type of failure occurs. Hence, surface crack detection on structures is important to on-line and in-service inspections of metallic components. 

There are many conventional nondestructive testing (NDT) methods used for interrogating metal surfaces; however, each method possesses certain limitations and disadvantages. Acoustic emission, dye penetrant, eddy current, ultrasonics, radiography techniques, and magnetic particle testing are examples of these techniques. In some environments, the technique used may not be optimum, but the only one that can be applied.

Since the late sixties, researchers have attempted using microwaves for surface crack detection in metals achieving modest success. None of these techniques, however, have dealt with filled and covered cracks. In addition, these techniques have not shown crack characterization capabilities such as dimension determination, tip location identification, etc. They have also been mostly experimental efforts with little rigorous modeling work. Microwave signals are not able to penetrate inside a conducting material due to their limited skin depths. However, they are well suited for interrogating surface perturbations such as surface cracks in a metallic structure.

Recent discoveries in using open-ended rectangular waveguides for microwave surface crack detection and sizing have generated interest. The foundation, potential, advantages and disadvantages of this methodology, developed at the Applied Microwave Nondestructive Testing Laboratory (AMNL) in the Electrical Engineering Department at Colorado State University, are discussed. Microwave techniques in general and this particular approach offer certain unique advantages that can advance the state of the art of fatigue/surface crack detection. (See box.)

The basic features and capabilities of this technique have been theoretically and experimentally investigated these past few years. However, more developmental work is needed to bring this technique from the laboratory to the real testing environment.

Technical approach

Microwave signals can penetrate inside dielectric materials and interact with their inner structure. This makes them excellent candidates for nondestructively inspecting dielectric media for detection of defects and material property characterization. However, for highly conducting media such as metals microwave signals undergo a complete reflection at the surface. Hence, they disclose only surface features such as surface cracks and roughness.

The basic idea behind our work is that without a crack the metal surface under investigation becomes a short circuit with very well known characteristics. However, with a crack present higher order modes are generated (i.e. surface currents are disrupted).

The characteristics of the reflected
wave inside the waveguide will change. Therefore, strategic probing of the fields inside the waveguide, as a cracked surface is being scanned, renders information. The crack can be detected by using either: a) the effect of the reflected dominant mode signal (from the crack), or b) the effect of the reflected higher order modes. The results for both cases have been very encouraging. Cracks with widths of less than 3 microns have been consistently detected at frequencies of less than 40 GHz. The signal-to-noise/clutter ratios associated with these two types of detected signals are greater than 10 dB. This holds true even for cracks only a couple of microns wide. Furthermore, the characteristics signal associated with a crack can determine the width, depth and the length of it.

Figures 1a-b show the relative geometry of an open-ended waveguide and a crack. Figures 2a-b show a metal surface coated with a single layer and a multi-layered dielectric coating. In both cases, the crack may be filled with a dielectric material as well. A microwave signal, generated by an oscillator, feeds a rectangular waveguide which is terminated by the metal surface under test. The signal reflected by the metal surface interferes with the incident signal. It then forms a standing wave in the waveguide. The standing wave experiences a shift in location when a crack enters the waveguide aperture. This shift is then detected via a simple detector diode.

The correct positioning of the diode can significantly improve its detection sensitivity. "Crack characteristic signal" refers to the detector voltage variations as a function of scanning distance, δ, when a crack is scanned over a waveguide aperture. Figure 3 shows an experimentally obtained (dashed line) crack/slot characteristic signal for a crack with a width of 0.55 mm and a depth of 2.5 mm at 24 GHz. Each crack characteristic signal is unique to the given crack dimensions, the operating frequency and the waveguide dimensions. Therefore, "characteristic signal" is an appropriate name. This voltage as a function of δ not only indicates the crack’s presence (detection), it also tells the crack’s width, depth and length (characterization).

**Crack sizing**

While the crack is outside the waveguide aperture, the diode registers very little voltage variation. This is because the waveguide is terminated by a relatively good short circuit. As the crack begins to appear within the waveguide aperture, the voltage experiences a rapid magnitude change. This is an indication of a rapid phase change in the reflection coefficient at the aperture. The rapid voltage change is an indication of one edge of the crack.

The same phenomenon occurs when the crack leaves the waveguide aperture (indication of the other edge). The voltage value does not change very much while the crack is inside the aperture.

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**Advantages of this method and other microwave techniques**

1. Novelty of the approach compared to conventional NDT techniques. This is a fresh look at fatigue crack detection and sizing. The yet to be tapped capabilities of this technique, once fully developed, have the potential of making it popular and a commonly used method for crack detection and analysis.
2. The method is fast, reliable and relatively inexpensive.
3. The sensor may or may not be in contact with the surface under examination offering the possibility of remote inspection.
4. Cracks may be filled or covered with dielectric materials such as paint, dirt, rust, etc.
5. The same probe which detects and characterizes the properties of a crack under coating, may also (without any alteration to its design) measure the thickness of the coating and its material characteristics.
6. Cracks may be on non-ferromagnetic as well as ferromagnetic metals or alloys.
7. Cracks on the surface of graphite composites may also be detected and characterized.
8. Microwave techniques work with coarse-grained materials.
9. The surface under examination may be in a high temperature environment.
10. The detected signal is only due to surface defects and not to interior flaws. Hence, signal interpretation is easier compared to techniques in which one must discriminate between signals due to interior and exterior flaws.
11. The technique may be applied to curved and other complicated surfaces.
12. The dimensions of a crack can be closely estimated.
13. Crack orientation, edge and tip locations can be detected.
14. No special operator skill in the fields of microwaves or signal interpretation, are needed for successful crack detection.
15. Very little (if any) surface preparation is required.
16. The technique is environmentally compliant and operator friendly and safe.
17. The required microwave power is in low milliwatt range.
18. Such a system may be battery operated and portable.
19. The results are obtained in real-time.
20. The technique is not a source of high electromagnetic noise pollution (Interference), and at the same time it is insensitive to external electromagnetic sources of interference. These two feature allow testing of a specimen during its normal operating conditions, thus reducing repair related down time.
21. Capability of inspecting large areas in a relatively short time (e.g., use of sensor arrays).
22. Detects in laminates and thick composites (disbond, void, inhomogeneity, impact damage, under cure, fiber bundle orientation and breakage, etc.) covering a metal specimen may also be detected and evaluated.
23. Adaptable to automatic (no operator involvement) detection routine.
24. A covered crack may be detected easier than an exposed crack.
25. Theoretical modeling provides for prior-to-detection measurement parameter(s) optimization. — CHARZ

**Disadvantages of using the microwave detection method**

- not applicable to cracks within a conductor.
- mathematical derivation not applicable to closed cracks.
- scan direction dependent.
- sensitive to variations in thickness.
- surface roughness may reduce detection sensitivity. — CHARZ
However, its value is still different than that of a short circuit case.

The distance between the voltage reversals for different cracks is primarily a function of crack width. (Although depth plays a minor role as well.) The signal level in the middle of the crack characteristic signal is a function of both the crack depth and width. After the crack’s width is estimated, the signal level in the middle of the crack characteristic signal can estimate depth. However, a swept frequency approach may render depth information independent of how accurate the width has been estimated.

**Mathematical models**

This problem can be modeled from an electromagnetic point of view using two distinct approaches. Utilizing these theoretical formulations, the experimental results have been successfully replicated. The models allow for predicting the crack characteristic signal for a given crack at a certain frequency. Hence, they enable the optimization of experimental parameters for enhanced crack detection and characteristics evaluation.

The first model developed at amnl employs a mode matching approach. To calculate the theoretical crack characteristic signal, appropriate boundary conditions at the waveguide aperture are applied. These conditions depend on the relative position of the crack within the waveguide aperture.

The field equations are satisfied through an expansion in terms of unknown coefficients and the eigenfunctions of the waveguide and the crack. These expansions are set up for the waveguide and the crack domains. A Fourier boundary matching approach is applied. The resulting calculation time depends on the number of higher order modes considered.

The smallest number of higher order modes necessary to produce a good theoretical crack characteristic signal depends on the crack dimensions, the waveguide dimensions, the relative location of the crack within the waveguide aperture, the operating frequency and the desired accuracy. Using this approach, you need a different code for a crack totally inside the waveguide aperture or at the edge, or for finite cracks.

The second model employs a moment solution approach. This approach utilizes the method of...
characteristic signals is very good. The slight deviations are due to a limited number of modes used in the calculation, the imperfection in machining a crack/slot in a metal specimen as specified and the detector diode characteristics.

**Filled cracks**

Filled cracks are common occurrences in steel bridges and other metallic structures. Hence, it is very important to be able to detect cracks filled with dielectric materials. The properties of the crack characteristic signal for an empty crack have been documented. However, when the crack is filled with a dielectric material its crack characteristic signal changes. The change occurs because a filled crack can be considered as a cavity with different resonant characteristics. This causes a reduction in the width of the crack characteristic signal.

Furthermore, a filled crack has a longer electrical depth than an empty one. This is the main cause for the signal level change in the middle of the crack characteristic signal. Figure 4 shows the measured crack characteristic signals for a crack/slot with a width of 0.51 mm and a depth of 1 mm, recorded at 24 GHz, when empty and when filled with rust powder. The reduction in the signal’s width (distance between the two sharp transitions), and the change in the middle level of the signal are evident. Figure 5 shows the calculated crack characteristic signals for a crack/slot with a width of 0.84 mm and a depth of 1.53 mm when empty and when filled with a dielectric material ($\varepsilon = 2 - j0.2$). The calculated results also follow a similar trend.

**2D crack characteristic signals**

To demonstrate the capability of using an open-ended waveguide for crack detection, a two-dimensional scan was performed. It was done on a milled crack/slot with a width of 0.3 mm, and a depth of 2 mm at 24 GHz. The purpose is to demonstrate how microwave images of cracks can be generated. Figure 7 shows the two-dimensional crack characteristic signal of this crack.

From this image, you can obtain the crack geometry information, such as orientation, length, width and depth. The change in signal level, a crack tip is indicated by the reduction in signal level, a crack tip is indicated by the change in signal level. The signal level will decrease.

**Comparing theory and measurement**

To show the validity of the moment solution approach, the calculated and measured crack characteristic signals are compared as shown in Fig. 3. The agreement between the two crack characteristics is very good. The slight deviations are due to a limited number of modes used in the calculation, the imperfection in machining a crack/slot in a metal specimen as specified and the detector diode characteristics.
cracks covered with dielectric coatings. Again, for covered cracks the development of a theoretical code will assist in choosing optimized measurement parameters. The sensitivity of this method has shown to vary as a function of the operating frequency.

Conclusions
The microwave method described has proven to be very effective in detecting and characterizing surface cracks in metals. It is inexpensive and can readily be applied in various environments. This approach applies to exposed, empty, filled and covered cracks. Cracks may also be detected remotely (i.e. the use on a liftoff in between the waveguide aperture and the surface under examination).

Field distribution
The tangential electric fields must vanish over the conducting surfaces; whereas they must be continuous over the aperture. To show the versatility of the moment solution approach, the tangential electric field distribution over the waveguide aperture for a finite crack is evaluated. The finite crack is located in the middle of the waveguide at the relative coordinates x = 2.5 mm and y = 1 mm (refer to Figure 1b), respectively. The electric field distribution is shown in Fig. 8. As expected, the field approximates zero over the conducting surfaces in the waveguide aperture. However, more modes would be needed to further reduce the ripples.

Higher order mode detection scheme
Changes in the dominant mode characteristics of a waveguide can be used for crack detection. Another method involves the detection of higher order modes at the waveguide aperture. A probing antenna located along the narrow dimension of the waveguide, close to the aperture, picks up the electric field magnitude. This is due to the higher order modes.

In the absence of a crack, there are no higher order modes present. Theoretically, the magnitude of the measured signal associated with higher order modes is zero. However, the presence of a crack generates higher order modes; subsequently, a finite amount of signal is measured. Hence, theoretically a signal-to-noise ratio (SNR) of equal to infinite is achieved.

This method is also applicable for...