# IDENTIFICATION OF DISTRIBUTED FATIGUE CRACKING BY DYNAMIC CRACK-CLOSURE

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## INTRODUCTION

Early fatigue damage is typically a distributed phenomenon affecting the structure at many locations. Multiple-site crack initiation and growth occur at numerous points of stress concentration, e.g., at rivet holes in a wing panel. Coalescence of such relatively large cracks can lead to sudden fracture, and may occur at loads significantly below what would be expected from considering the fracture resistance of single cracks [1,2]. Under laboratory conditions, a great variety of NDE techniques are available for early fatigue damage detection and characterization. These techniques include acoustic emission, linear and nonlinear ultrasonics, vibration analysis, eddy current inspection, magnetics, thermal imaging, X-ray, etc. Unfortunately, most of these methods cannot be directly adapted to in-field inspection of aging aircraft. One reason for this is that the most sensitive ultrasonic and eddy current methods are essentially short-range, localized measurements. On a large airframe structure, their use is limited to the inspection of a few suspected areas of high stress concentration, but they tend to loose sensitivity very rapidly when applied to distributed and multiple-site cracking. Large-scale, overall inspection has inevitably lower sensitivity to distributed multiple-site cracking, especially in the presence of artifacts causing false alarms. Strong artifact signals are caused by uncertainties in the inspection procedure (e.g., coupling in ultrasonic testing or lift-off in eddy current testing), inherent geometrical features (e.g., nearby holes and edges), and additional irregularities (e.g., uneven machining, mechanical wear, corrosion, etc.). There seems to be a need for specialized long-range ultrasonic and eddy current techniques which do a better job at distinguishing real fatigue cracks from inherent structural and material variations. These techniques need to be fine-tuned to characteristic features exhibited by fatigue cracks and only fatigue cracks. First, we shall demonstrate that crack-closure under external deformation can be exploited to achieve significant improvements in the threshold sensitivity of long-range ultrasonic and eddy current inspection methods. Second, we shall demonstrate the feasibility of producing dynamic crack-closure by localized cooling with a commercial freezing spray.

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## INCREASED SENSITIVITY DUE TO CRACK-CLOSURE

In the following we present preliminary results to demonstrate the underlying physical phenomena and to illustrate the potential benefits of the suggested methods. For this purpose, we prepared a pair of model specimens that simulate some of the above mentioned features which make it difficult to use conventional NDE techniques for large-scale inspection. Both specimens were machined from 2024-T351 aluminum bars of 1/2"x1" cross-section and had three 1/4"-diameter "rivet" holes. The edge of one of the rivet holes was deliberately chipped off to simulate an artifact on the "intact" reference specimen. The other specimen was fatigue cycled in bending to produce fatigue cracks between two of the rivet holes. The cracks were app. 1 and 4 mm long and readily detectable by close visual inspection. These cracks were also easily detected by high-sensitivity ultrasonic and eddy current probes during close-range inspection. Figure 1 shows the schematic diagram of long-range inspection for multiple-site fatigue cracking by (a) ultrasonic and (b) eddy current sensors. In the following we shall demonstrate that long-range inspection by conventional methods could not distinguish the fatigue cracks from the spurious artifact signals in these specimens and propose simple modifications to improve the detectability of fatigue damage. From practical considerations, long-range overall inspection is preferable in field testing of aircraft structures. However, the inevitable drop in sensitivity and increased susceptibility for artifact signals can both increase the number of missed defects and that of false alarms. Often, this is too high a price to pay for the convenience of long-range inspection. Then, we can take advantage of the crack-closure phenomenon to positively identify real flaw signals associated with partially closed fatigue cracks.

Figure 2 shows typical ultrasonic signals from the intact and damaged specimens at different levels of bending loads applied to the 10"-long specimens. In this experiment, a 2.25-MHz, 1/2"-diameter Rayleigh wave wedge transducer was used at app. 20 mm distance from the damaged holes. Although fatigue cracks tend to originate from the surface and therefore surface wave inspection is especially sensitive to such cracks, very similar experiments can be done with either longitudinal or shear wave transducers, too. Naturally,

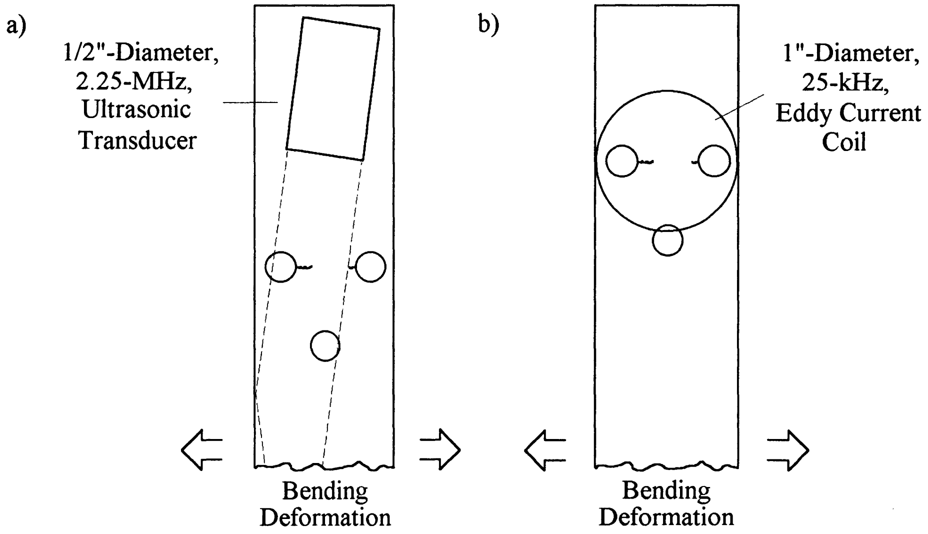

Figure 1. Long-range inspection for multiple-site fatigue cracking by (a) ultrasonic and (b) eddy current sensors.

uncertainties in the alignment and positioning of the transducer cause significant variations in the detected signals during long-range inspection and rather different echo patterns can be obtained from the same general location and direction. In this particular case, there seems to be an even larger flaw signal reflected from the chopped-off edge of one of the rivet holes in the intact specimen than from the fatigue cracks in the damaged one. Consequently, depending on the threshold setting of the flaw detector, either a false alarm will occur in the intact specimen or the defect will be missed in the damaged one.

Much better results can be achieved by monitoring the stress-dependence of the echo pattern from the specimen. This rather complicated pattern can be regarded as the fingerprint of the specimen that is related to the detailed geometry of the specimen, but the relation is usually too complex to evaluate. On the other hand, any significant change in this characteristic signature under external deformation is a telltale indication of crack-closure somewhere in the structure. Figure 3 shows the differential ultrasonic signals from the intact and damaged specimens at different levels of bending loads. The same raw data was plotted in Figure 2, but here we subtracted from each signature the corresponding signal recorded in the undeformed state. Thanks to this very simple signal processing technique, the fatigue crack becomes quite apparent as it is the only non-stationary part of the signature.

Clearly, one of the most characteristic features of fatigue cracks, which can be used to distinguish them from other types of discontinuities, is that they are partially closed by residual stresses and the opposite surfaces match fairly well each other so that they can be easily closed further by the application of modest external deformations. The previously described acoustic method was based on the parametric modulation of the otherwise linear ultrasonic wave scattering by the changing interfacial stiffness of the closing or opening crack. Regardless whether we measure the ultrasonic velocity in a specimen having clusters of microcracks or the scattering from large individual cracks, the crucial point is the changing mechanical contact between the opposite faces of the cracks. Naturally, any other, not necessarily mechanical, method which is sensitive to this changing contact would also reveal the presence of fatigue cracks. For example, it is well known that the electrical resistance through compressed surfaces is very sensitive to the interface pressure. In this way, the eddy current response of a cracked specimen is expected to change much more under external deformation than that of an intact specimen. This effect can be exploited to distinguish between small signals caused by real fatigue cracks and other features which can cause spurious indications but do not exhibit the revealing crack-closure effect. It is expected that the electromagnetic crack-closure effect can substantially improve the sensitivity and reliability of eddy current inspection on large structures of complicated geometries.

Figure 1b showed the geometrical configuration of long-range eddy current inspection. The same multiple-site fatigue damaged specimen was used as in the previous crack-closure experiment. A large 1"-diameter pancake coil was used at 25 kHz where the skin depth is app. 0.6 mm. The specimen was vibrated at 1.3 Hz with a load corresponding to app. 10% of the load previously used during fatigue cycling. Careful inspection with a 2-mm-diameter, 500 kHz probe could clearly reveal both fatigue cracks extending between the simulated rivet holes. Due to the awkward shape of the specimen (closeness of holes and edges), the low-resolution eddy current inspection was unable to positively identify the two relatively large (4- and 1-mm-long) cracks. In comparison, the dynamic eddy current responses of the two specimens were very different due to the strong crack-closure effect observed on the damaged specimen. Figure 4 shows the detected eddy current signals from the intact and fatigue damaged specimens with a 1"-diameter coil at 25 kHz. The eddy

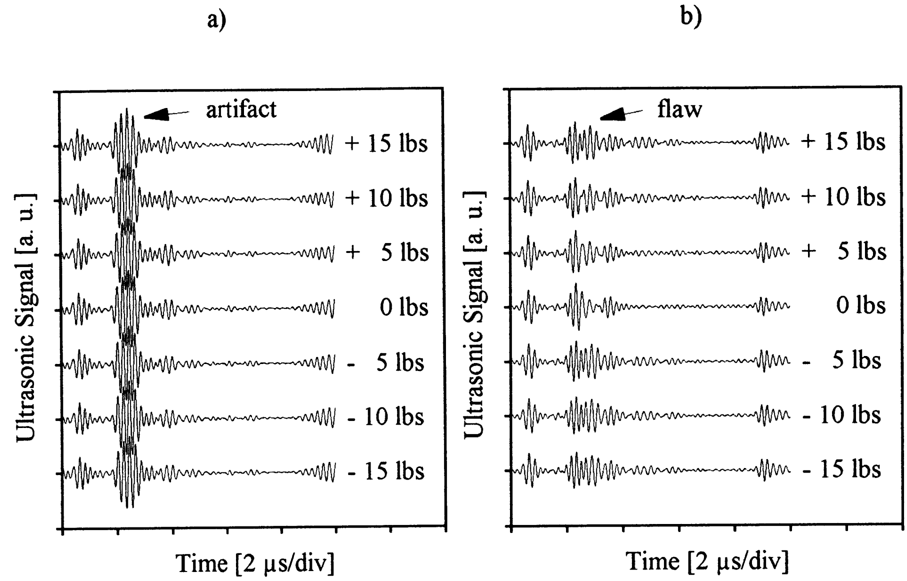

Figure 2. Typical ultrasonic signals from the (a) intact and (b) damaged specimens at different levels of bending loads.

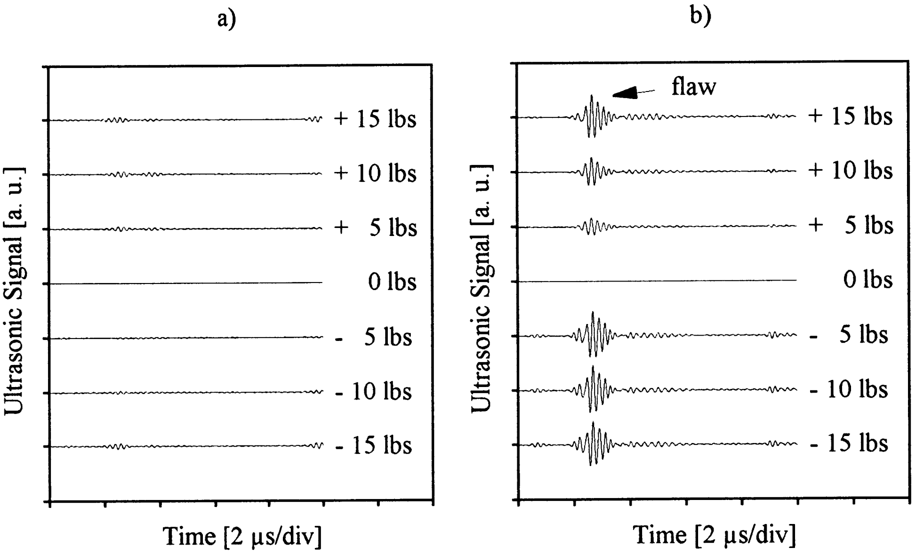

Figure 3. Differential ultrasonic signals from the (a) intact and (b) damaged specimens at different levels of bending loads.

current signal was high-pass filtered at 0.1 Hz to eliminate the dc component which greatly depends on the relative position of the probe with respect to the nearby holes and edges. The undamaged specimen showed only minor modulation at the vibration frequency and its second harmonic. The observed very weak variation was probably due to the inevitable lift-off effect. In comparison, the damaged specimen exhibited very strong modulation mostly at the basic harmonic. The asymmetric distortion of the observed modulation indicates a significant second harmonic which is mainly due to the asymmetry of the crack-closure phenomenon itself.

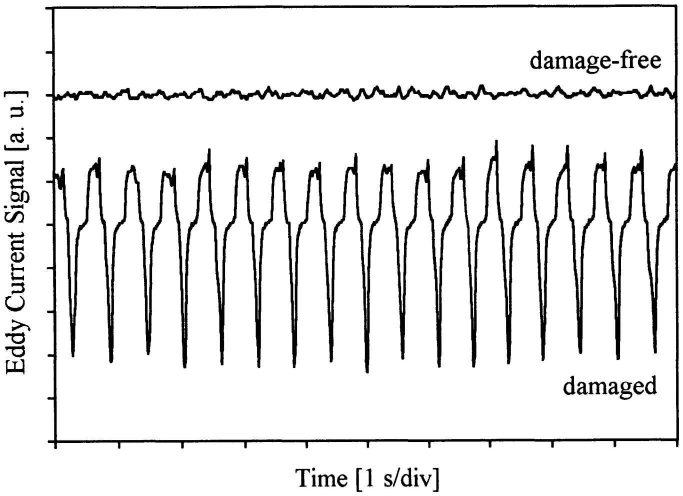

Figure 4. Detected eddy current signals from the same intact and multiple-site fatigue damaged specimens used in the previous crack-closure experiment (1"-diameter coil, 25 kHz).

## DYNAMIC CRACK-CLOSURE BY COOLING

The technical realization of the suggested dynamic signature analysis method can take numerous forms. In the simplest version of this approach, the external deformation required to produce crack-closure is provided by vibrating the whole structure at a few Hertz. The detected rf wave form is continuously subtracted from its most recent average over the last few seconds. Such simple signal processing is readily available from most state-of-the-art digital flaw detectors. By subtracting the stationary part of the ultrasonic signature, only the alternating part is retained [3]. This dynamic component of the signature is mainly caused by crack-closure. Naturally, more sophisticated techniques are also available for increasing the sensitivity and selectivity of the method. By correlating the external deformation to the observed dynamic signature we can reduce the adverse effects of unrelated changes in the signal. For example, in the case of periodic loading at a particular frequency, only that part of the dynamic signature is attributed to crack-closure which has the same or double frequency, while other changes of different frequencies caused by unrelated instabilities in the measurement are neglected.

An alternative way to produce the elastic deformation needed for crack-closure is by cooling or warming. It is well known that temperature variations can lead to extremely high levels of internal stresses in materials having constituents of different thermal expansion coefficients. For example, in a metal matrix composite strong static stresses can be produced just by slowly cooling or warming the specimen. Of course, the same approach would not work in homogeneous materials such as an aluminum alloy aircraft structure. However, dynamic thermal stresses can be still produced by rapid and concentrated cooling and heating. These stresses are temporary only as they disappear as the temperature gradients vanish due to the thermal conductivity of the material.

We have tried various ways of applying rapid localized heating and cooling to aluminum specimens. We found that the easiest and most effective way to produce the necessary temperature gradients is by using a commercially available FreezIt® cooling spray. According to our measurements, app. 100 W cooling power can be delivered in this way to a small spot of app. 1/10" in diameter. We have used this technique to temporarily deform a series of 6"x1"x1/2" 2024 Aluminum bars containing fatigue cracks. The deformation has two principal contributions which can be separated easily based on their different time-dependence. Figure 5 illustrates these two deformations in a schematic way. First, there is a bending deformation caused by the through-thickness temperature gradient. Second, there is "necking" deformation caused by the axial temperature gradient. Figure 6a shows the end displacement of the bar caused by the through-thickness temperature gradient. The deformation is almost instantaneous and maintained throughout the cooling. Figure 6b shows the internal temperature at the center during and immediately after cooling.

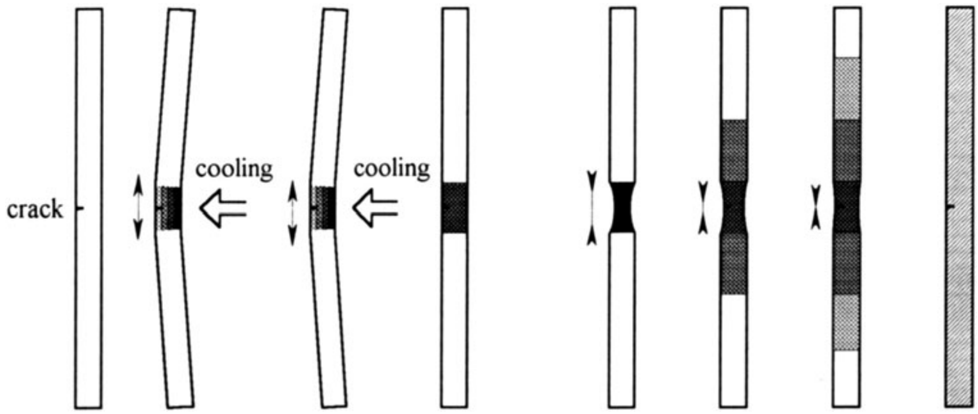
a) b)

Figure 5. Initial crack-opening (a) caused by the bending due to the through-thickness temperature gradient and subsequent crack-closure (b) caused by the necking due to the axial temperature gradient.

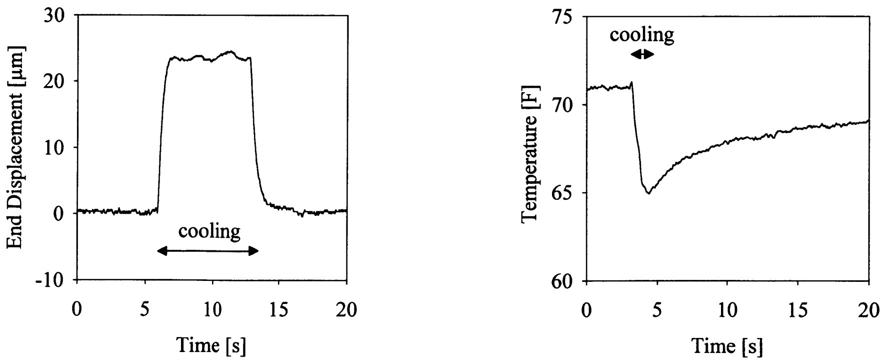
a) (b)

Figure 6. End displacement (a) caused by the through-thickness temperature gradient and internal temperature (b) at the center during and immediately after cooling (6"x1"x1/2", 2024 Aluminum bar).

During cooling the temperature rapidly decreases. Afterwards, the temperature exponentially increases with a time constant of app. 5 s until it equalizes over the hole length of the specimen. Naturally, there is also an additional, much slower warming as the specimen returns to the ambient temperature via thermal conduction through the surrounding air.

Figure 7 shows the effect of initial crack-opening and subsequent crack-closure on the ultrasonic reflection from four specimens listed in Table 1. The measurements were made with a 5 MHz surface wave transducer. The cooling spray was applied for app. 1.5 seconds at the opposite side of the specimen. The signal from the reference specimen was strong but remarkably stable. The signals from the other three specimens exhibited a distinctive modulation upon cooling. The characteristic shape of the modulation clearly corresponds to the combined effects of the previously discussed two deformation components. The instantaneous bending deformation causes crack opening thereby increasing the ultrasonic reflection from the crack. The subsequent necking deformation causes a lagging crack-closure thereby decreasing the signal for a substantial time after the cooling. This modulation readily reveals the presence of partially closed fatigue cracks in the specimen. The strength of the modulation apparently increases with the length of the fatigue cracks. Figure 8 demonstrates the effect of the inspection frequency on the strength

Table 1. List of the fatigue specimens used in this study.

| I.D. | type | cycle* | length |
|---|---|---|---|
| ref. | saw-cut | n/a | 3 mm |
| #8 | fatigue crack | 1.73 $10^5$ | 0.61 mm |
| #9 | fatigue crack | 1.69 $10^5$ | 1.25 mm |
| #10 | fatigue crack | 1.73 $10^5$ | 1.75 mm |

* max load 28.6 ksi, load ratio 0.9, frequency 29 Hz, 2024 Al

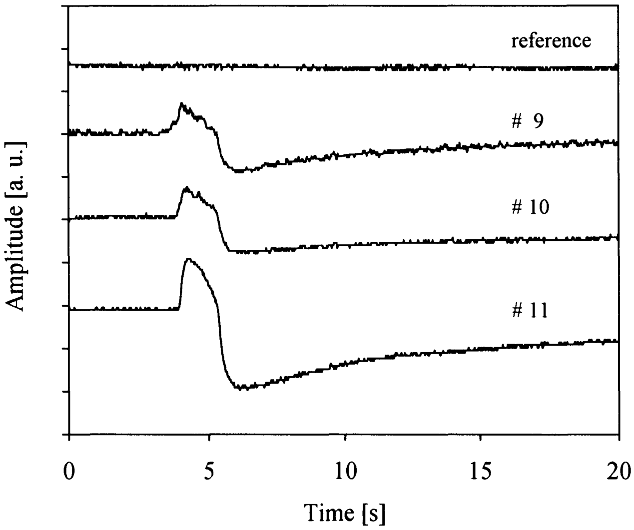

Figure 7. The effect of initial crack-opening and subsequent crack-closure on the ultrasonic reflection from four specimens listed in Table 1.

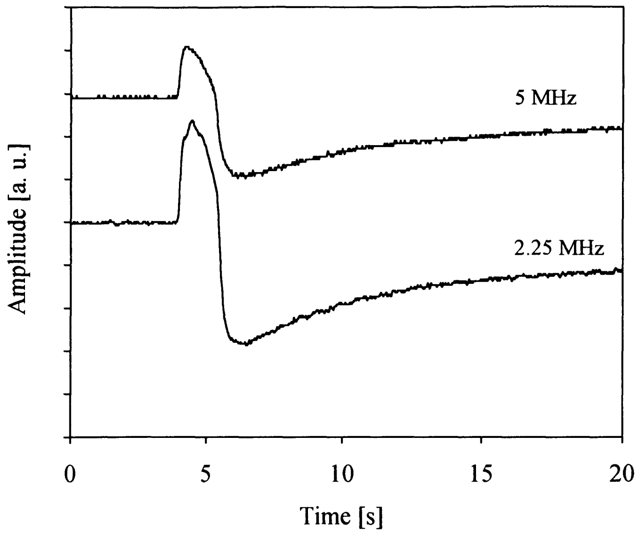

Figure 8. The effect of the inspection frequency on the strength of the amplitude modulation (surface wave inspection, sample #11).

of the amplitude modulation through the example of sample #11. Although the signal itself increases with frequency, the dynamic modulation due to the thermally induced crack-closure is stronger at lower frequency.

## CONCLUSIONS

Conventional materials characterization and nondestructive evaluation techniques have to be modified to adapt them for detection and quantitative assessment of fatigue damage in different materials and structures. These modifications can take advantage of the characteristic features of fatigue damage and greatly enhance the sensitivity, accuracy and reliability of testing. Crack-closure can be used to identify fatigue cracks in both ultrasonic and eddy current measurements. Dynamic crack-closure can be produced by mechanical deformation as well as by thermal excitation. It was demonstrated that cooling by a commercially available freezing spray can be used to produce temporary crack-opening and -closure for fatigue crack identification.

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