ULTRASONIC IMAGING OF CRACKS UNDER INSTALLED FASTENERS

K. I. McRae and R. W. Nolan
Air Vehicles Research Detachment
National Defence Headquarters
Ottawa, Canada K1A OK2

INTRODUCTION

A variety of conventional NDI techniques, such as visual inspection, radiography, eddy current and ultrasonics, have already been developed and implemented to detect fatigue cracks in aircraft structures. There is a continuing requirement to decrease the minimum detectable crack length so as to assure detection prior to crack criticality and component failure. It is often necessary to detect small fatigue cracks under the fastener head without prior removal of the fastener from the structure [1-3]. The location of the crack initiation site is dependent upon the local stress distribution in the vicinity of the fastener and the surface condition of the hole and the countersink, but may generally be considered to occur at one of three possible sites: at the countersink, at the faying surface or in the bore of the fastener hole. Despite a significant, long term level of activity, a fast, reliable means of detecting partially or totally obscured fatigue cracks at these sites without the removal of the fastener does not exist.

Several specific techniques within the broader categories of eddy current and ultrasonic methods have been developed to detect and measure cracks under installed fasteners. Research in the area of eddy current detection of cracks under fasteners has made significant progress. Two commercial devices, the Nortec Eddyscan [4] and the Northrop Low Frequency Eddy Current Array (LFECA) [5], have been developed for this purpose. The eddy current techniques are able to detect relatively small flaws and can detect flaws beyond the first layer in multi-layer lap joint configurations. A limitation of the eddy current technique arises if the required inspection involves fasteners made from ferrous materials. In this case, strong signals from the fastener may completely mask or distort the response from small cracks and special techniques or instrumentation must be developed in order to accommodate this interference. It has also been determined that some ferrous fasteners possess magnetic anomalies that may produce false crack detection signals [6].

Development of ultrasonic techniques for the detection of cracks under fasteners has also been under way for a long period of time. An early and extensive study [7] resulted in the development of a small, hand-held rotary scanner, as well as a fully automated scanning device. A specific advantage to the ultrasonic technique is its relative insensitivity to fastener material. There are, however, some limitations to the application of automated
ultrasonic inspection techniques for routine fastener inspection. Instrument setup is time consuming and usually requires separate procedures for the countersink, mid-bore and faying surface regions. The devices tend to be relatively large and prohibit inspections of regions with limited access. Ultrasonic techniques are complementary to the eddy current techniques in that they allow detection of small cracks relatively deep within the material and, if properly configured, are insensitive to the presence of the fastener and to the fastener material.

SHEAR WAVE ULTRASONIC IMAGING

Previous studies concerning the application of ultrasonics to the detection and measurement of fatigue cracks under installed fasteners have identified a variety of experimental configurations and acoustic wave modalities. The early study conducted by Raatz et al. [7] identified the direct reflection from a fatigue crack using a high incidence angle (70°) shear wave as being the most effective technique for single transducer flaw detection. In this current effort, all scans were performed in a raster pattern in conjunction with a 70° shear wave. The scans were oriented such that the axis of the ultrasonic transducer is normal to the plane of the fatigue crack and parallel to the principle stress axis of the fatigue crack specimens described below. A schematic diagram showing the orientation of transducer with respect to the fastener is shown in Figure 1.

Figure 2. Result of modeling incident longitudinal and refracted shear waves (a) with the beam focussed on the specimen surface and (b) with the beam de-focussed by 12.5 mm.
Insonification of the specimen with a focussed ultrasonic beam in the vicinity of a fastener is more complex than would be implied above using a simple point source. Prior to performing any experimental work, the effect of interrogating the specimen with a focussed beam is examined through the use of a commercial ray-tracing program. If the incident ultrasonic beam of a highly focussed 25 MHz transducer is allowed to contact the specimen surface at the focal length of the transducer, a result similar to that shown in Figure 2(a) is obtained. This indicates that relatively poor depth of penetration at the expected depth of countersink can be expected. By de-focussing the transducer by 12.5mm (Figure 2(b)), the beam remains highly focussed to a greater depth within the specimen. Because of the relative complexity arising from this beam pattern, it is a significant advantage to correlate detected signals with structural details through the use of ultrasonic imaging. No further attempt is made to determine the precise origin of the multitude of signal obtained from the flaw and the fastener bore.

FATIGUE CRACK SPECIMENS AND DATA ACQUISITION

A total of 58 fatigue crack specimens were manufactured from 0.330" thick 7075-T651 aluminum plate. Each specimen contains three fastener holes and each fastener hole typically contains two fatigue cracks at the countersink, at the faying surface or at the mid-bore of the fastener hole. The fastener hole geometry is shown schematically in Figure 3. Fatigue cracks were generated by first drilling a small pilot hole, fatiguing the specimen under axial loading followed by boring the final fastener hole and countersink. All fatigue cracks were measured microscopically during the crack generation process and span a range of radial crack lengths from 0.008" to 0.300". The details of the specimen design and the method of preparation have been reported elsewhere [8].

All ultrasonic data were acquired using conventional, immersion C-scan instrumentation and a highly focussed 25 MHz transducer. Full waveform C-scan data sets were obtained by scanning the transducer in a square raster pattern with dimensions 1" x 1" centered over the fastener. This was accomplished by acquiring a 256 element A-scan, sampled at 8-bit resolution, at each point on a 256 x 256-element C-scan grid. Care was taken to orient the known crack plane to be normal to the transducer axis. All images were obtained using a broad acquisition gate in order to accommodate reflections that are time variant.

![Figure 3. Fastener hole and specimen thickness dimensions for fatigue crack specimens](image-url)
ULTRASONIC IMAGES OF UNFLAWED SPECIMENS

The large number of reflected ultrasonic signals that are obtained during the data acquisition process further complicates their interpretation. Analysis of individual A-scan signals is virtually impossible in the absence of some means of correlating the acquired signal to the structure of the specimen. This relative complexity arises from several factors. The propagating shear wave that is used to insonify the specimen in the vicinity of a fastener may interact with a large number of surfaces. Multiple mode conversions of the incident and reflected waves are also possible. The use of ultrasonic imaging allows the spatial correlation of the acquired signal with the corresponding structural detail without a precise interpretation of the signal source. A detailed knowledge and interpretation of individual A-scan signals is not required and the precise nature of the signal has not been determined.

Ultrasonic images of an unflawed fastener specimen, without and with the fastener installed, are shown in Figure 4(a) and 4(b), respectively. In the case where no fastener is present, the acquired image is relatively easy to interpret and contains reflections from the countersink, from the edge of the borehole and from the countersink – bore shoulder. By inserting the fastener, the image changes somewhat due to the change in structural detail. A signal from the edge of the fastener is detected, while the bore and countersink reflections are no longer detected.

FLAW DETECTION AS A FUNCTION OF FLAW LOCATION

As mentioned above, the problem of detecting small fatigue cracks originating at fastener holes in relatively thick wing skin material can be further categorized by three regions of interest: the countersink region, the mid-bore of the fastener and the faying surface. In order to determine the effect of the fastener and the detectability as a function of flaw depth, ultrasonic images have been obtained in each of these three regions in the 0.33” thick aluminum specimens, with and without the fastener installed.
The ultrasonic images shown in Figure 5 were obtained from a specimen with a small (0.020") fatigue crack occurring at the right side of the fastener (relative to the ultrasonic scanning axis). The small reflection that occurs off axis and to the right of the fastener bore reflection can be attributed to this fatigue crack. In the case where the fastener has been installed (Figure 5(b)), the small reflection from the fatigue crack is still detectable, however, it is not completely resolved from the reflection due to the edge of the fastener head.

It should be noted that this only occurs for small fatigue cracks that require a large gain increase, such as that shown in Figure 5. For larger flaws (>0.050"), the amplitude of the flaw reflection is much greater than that obtained from the edge of the fastener head and does not influence the detectability of the flaw. Interference of the diffracted signals from
the head of the fastener with the signal from the fatigue crack will, however, limit the detectability of small fatigue cracks in this region.

Fatigue cracks located in either the mid-bore or faying surface regions do not suffer from this interference. Figure 6 shows the ultrasonic images obtained from two relatively large fatigue cracks (left - 0.102” and right - 0.061”) that are located at the mid-bore of the specimen, with and without the fastener installed. It is noted that, although the pattern of reflections varies as a result of the presence of the fastener, there is virtually no difference in the reflections produced by the two flaws. It should also be noted that the size of the reflection does not accurately correspond to the actual flaw size; the reflection from the 0.061” crack is approximately the same size as the reflection from the 0.102” crack. It is unlikely, therefore, that this will result in an accurate crack size measurement technique.

The observation that the amplitude of the flaw reflection is not linearly related to the crack size is again reinforced by observation of Figure 7, which shows ultrasonic images obtained from small (left - 0.017” and right - 0.016”) fatigue cracks located at the faying surface of the fatigue crack specimen. The reflected amplitudes from the two flaws are extremely repeatable and there is no detrimental effect due to the presence of the fastener. Although the two flaws have almost identical crack lengths, the amplitude of the reflection and, hence, the detectability of the two flaws is significantly different.

CONCLUSIONS

Images of fatigue cracks were obtained by combining conventional C-scan techniques and a high incidence angle (70°) shear wave. Results obtained both with and without the fastener installed indicated that, although some of the image features may vary, the detectability of fatigue cracks is not strongly dependent upon the presence of the installed fastener. This is significant in that a fundamental disadvantage of complementary eddy current techniques is their relative sensitivity to the fastener material, particularly in the case of ferrous fasteners.

Figure 7. Ultrasonic images of a flaw with a 0.016” radial crack length at the faying surface of the specimen: (a) without the fastener installed and (b) with the fastener installed.
The ultrasonic technique can be implemented such that the detectability of small fatigue cracks is relatively high. The smallest fatigue crack that has been reliably detected thus far has a lateral crack length of only 0.014". This sensitivity is dependent upon the beam focal spot size at the flaw, however, a combination of beam profile modeling and current high frequency ultrasonic instrumentation is capable of achieving a high level of resolution. The sensitivity of the technique is also dependent upon the surface condition of the component.

This initial application was performed in order to investigate detectability of small fatigue cracks initiating from fastener holes and to determine the sensitivity to the presence of the fastener. The technique is not readily applicable to the inspection of a large number of fasteners because the scanning process is far too slow and requires long setup times. A continuing effort must develop techniques that will eliminate the mechanical scanning process, allow rapid orientation of the instrumentation with respect to the fastener and reduce the overall size of the device to allow easy use for on-aircraft inspection applications.

REFERENCES