DEVELOPMENT OF A ROTATING FERROMAGNETIC RESONANCE EDDY CURRENT PROBE FOR INSPECTING SMALL RADIUS CURVED SURFACES ON GAS TURBINE ENGINE COMPONENTS[1]

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INTRODUCTION

The Retirement-for-Cause (RFC) program has a target flaw size of 0.25 mm long x 0.13 mm wide that must be reliably detected in complex geometries such as the key slot in the jet engine interstage seal shown in Figure 1. A rotating eddy current probe has been developed in an ongoing exploratory development program for advanced NDE methods, which is based on a YIG (Yttrium Iron Garnet) ferromagnetic resonance (FMR) probe. This rotating probe is designed to inspect the small radius (1.8 mm) corners of the key slot. The FMR probe is utilized in an active mode in which it operates as the resonant element in an oscillator circuit (active FMR probe) at frequencies in the order of 800 MHz. A laboratory breadboard signal processor system has been fabricated which converts the active FMR probe output into voltage levels corresponding to it's frequency and amplitude. It has been demonstrated in previous

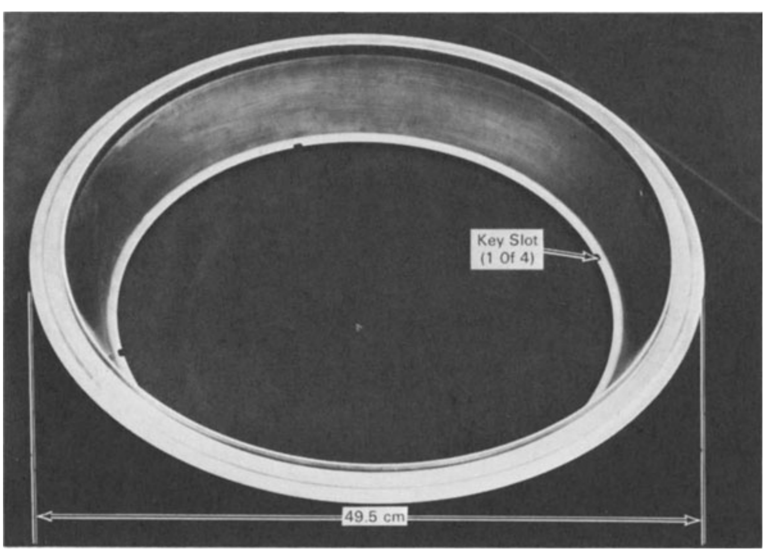

Fig. 1. Jet engine interstage seal component.

work[2] that flaw and liftoff information can be generated with phase separation from the frequency and amplitude of an active FMR probe. The data presented in this paper, however, is processed only from the amplitude signal. Due to the physical restrictions put on the fabrication of the small radius active FMR probe, we were unable to achieve flaw/liftoff separation by mixing the frequency and amplitude signals as in our previous work. However, we feel that flaw/liftoff separation from the physically small probes is possible with some redesign in the oscillator circuit.

SMALL RADIUS PROBE DEVELOPMENT

The development of the small radius probe was based on the requirement to inspect the key slot corner geometry shown in Figure 2. We chose a cylindrical probe geometry with a diameter of approximately 3 mm in order to fit into the 1.8 mm radius key slot corner and allow a rota-

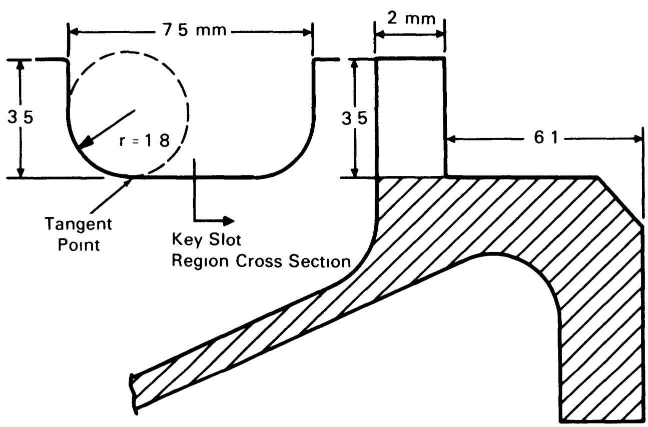

Fig. 2. Key slot geometry.

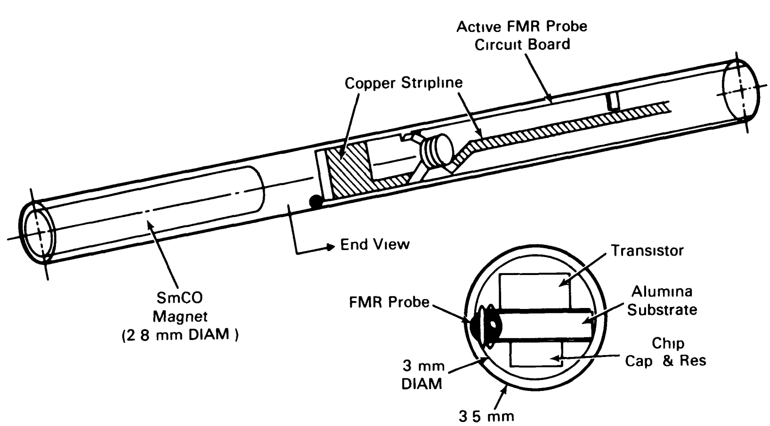

Fig. 3. Conceptual design of small radius probe.

tional scan with the active FMR probe. The conceptual design of the small radius active FMR probe is shown in Figure 3. This figure illustrates the hardware layout of the small radius probe and how the various oscillator components relate to the 3.5 mm diameter corresponding to the key slot corner. In the actual probe construction we used thin walled stainless steel tubing with a 3.3 mm O.D. as the active FMR probe body. A window was machined in the tubing wall to expose the FMR probe. The FMR probe consists of a 0.30 mm diameter YIG in a single-turn 0.38 mm diameter loop of wire. This arrangement gives the FMR probe an effective eddy current field diameter of approximately 0.38 mm, or the diameter of the loop.

The circuit diagram for the active FMR probe is shown in Figure 4. This figure illustrates the oscillator biasing and impedance matching techniques. The dc power for the oscillator is sent over the rf output line to reduce probe wiring. The stepped transmission line connecting the FMR probe with the transistor emitter was incorporated to allow oscillation for the lower FMR probe Q that resulted from the use of the physically small (2.8 mm diameter cylinder) permanent magnet.

ROTARY PROBE DEVELOPMENT

The rotary probe concept we chose for this application is shown in Figure 5. The active FMR probe and the microwave eddy current (MEC) signal processor are rotated while the slip ring assembly and the rotary probe housing are held stationary. Note that we also added a flat surface active FMR probe interchangeable assembly to demonstrate the flexibility of this concept.

The signal processor demodulates the amplitude and frequency of the active FMR probe output producing voltage levels corresponding to the amplitude and frequency of the 800 MHz signal. This allows the use of slip rings to transfer the data out of the rotating assembly. The MEC signal processor and active FMR probe block diagram is shown in Figure 6. The signal processor basically converts the 800 MHz probe output down to an intermediate frequency (IF) of less than 50 MHz for amplitude and frequency detection. Automatic frequency control (AFC) is utilized to hold the IF in the appropriate frequency range for the detectors. This feature is particularly important when several active FMR probes

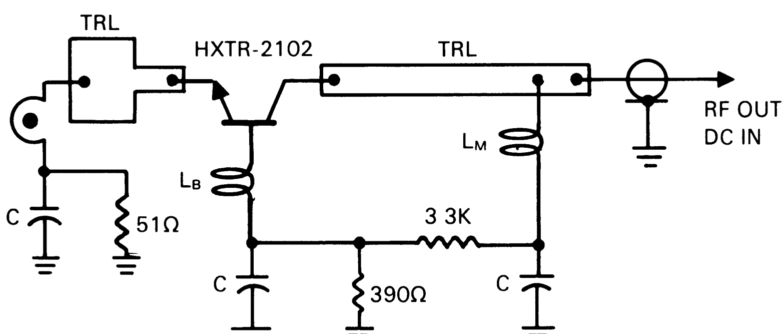

Fig. 4. Active FMR probe schematic.

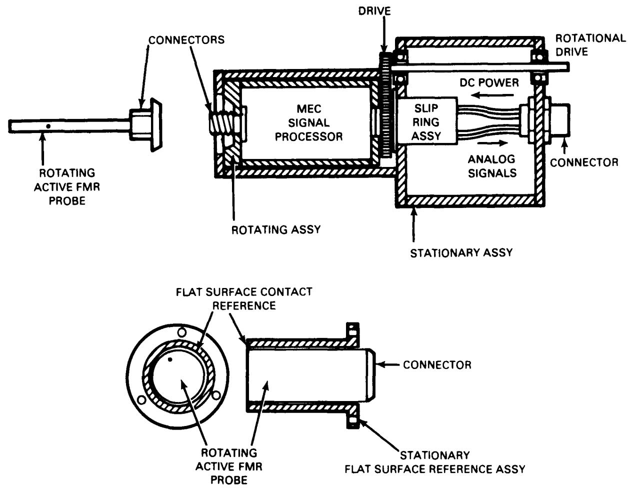

Fig. 5. Rotary probe conceptual design.

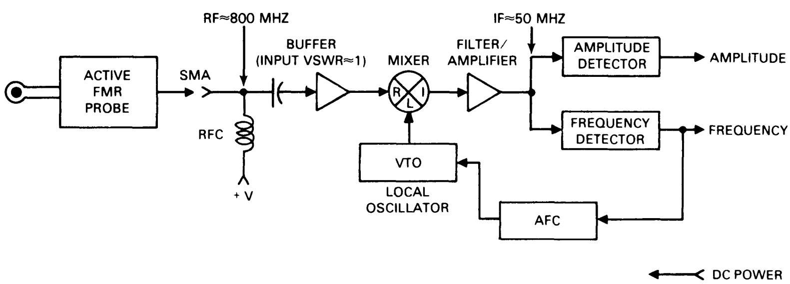

Fig. 6. Rotary probe signal processor block diagram.

are to be operated with the signal processor each having a different operating frequency.

The disassembled rotary probe is shown in Figure 7 with the small radius active FMR probe attachment. Not shown is the other half of the signal processor which is located on a circuit board directly behind the one shown.

LABORATORY EVALUATION

The rotary probe is shown in the key slot inspection fixture in Figure 8. The small radius active FMR probe is positioned into the key slot corner with precision slides. Rotational drive is provided by a stepper motor driven flexible cable. The rotational speed of the probe is approximately 1.5 revolutions per second. Data taken with this arrangement are shown in Figure 9. The top trace in each of these data examples is the demodulated amplitude signal out of the rotary probe and

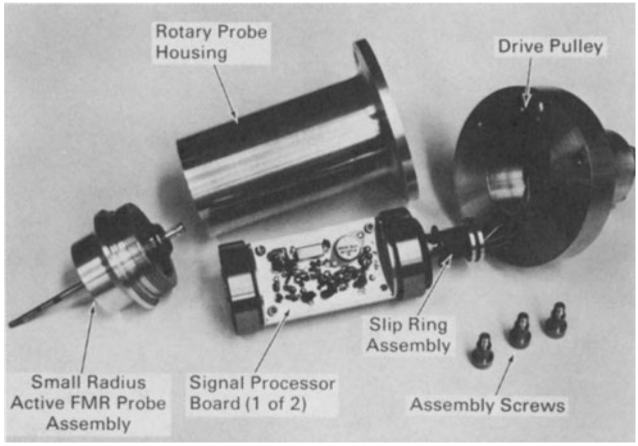

Fig. 7. Disassembled rotary probe.

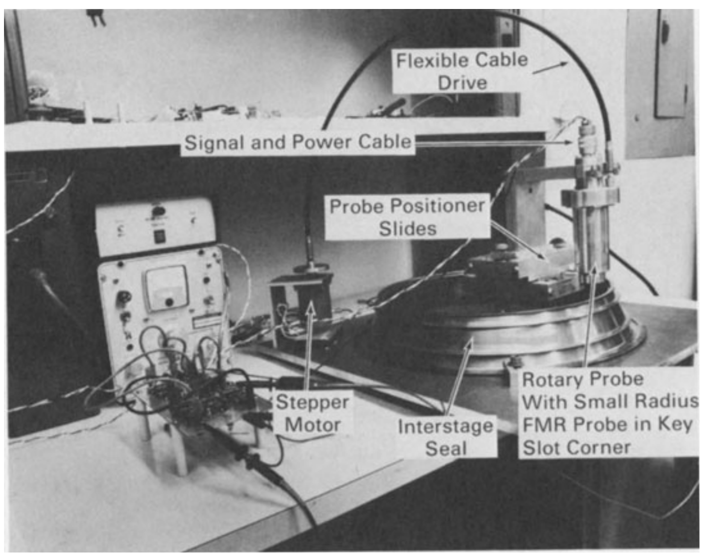

Fig. 8. Key slot inspection arrangement.

the bottom trace is the amplitude signal bandpass filtered at 12-20 Hz. The data in the upper example are simply the liftoff response of the probe to an unflawed key slot corner. The lower-left example data are the probe response to a 0.25 mm x 0.13 mm EDM notch (RFC target flaw size), which was fabricated in the middle of the key slot corner. The flaw responses shown in the lower-right example are a result of a 0.75 mm x 0.13 mm EDM notch fabricated at the tangent point of key slot corner. We attempted to detect a 0.25 mm x 0.13 mm notch fabricated near a targent point without success. The notch was fabricated slightly out of the key slot corner and away from the tangent, which apparently resulted

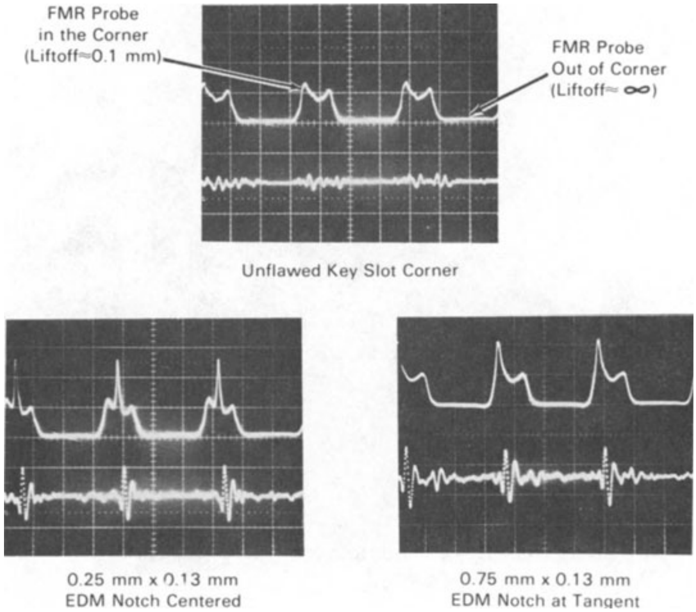

Fig. 9. Rotary FMR probe data from key slot corner.

in excessive liftoff at that point in the rotational scan. Note that the flaw response in these examples is of equivalent magnitude to the liftoff response of the probe going from air, or infinite liftoff, to inspection liftoff, which is in the order of 0.1 mm. It is evident from these data that the extremely high operating frequency of the FMR probe (800 MHz) does not result in unacceptable liftoff responses even to worst case liftoff variations. We feel this is in part due to the extremely small effective eddy current field diameter (approximately 0.38 mm) of this probe.

The rotary probe configured with the flat surface active FMR probe is shown in use in Figure 10. This figure illustrates the manual examination of a flat surface flaw specimen with the stationary probe housing in contact with the specimen surface. The rotating active FMR probe (refer to Figure 5 for flat surface probe concept) is recessed for a liftoff of approximately 0.1 mm. The scan radius of the FMR probe is approximately 4 mm. The FMR probe in this configuration consists of a 0.75 mm diameter YIG in a 1 mm single-turn wire loop.

Data taken with the flat surface probe are shown in Figure 11. These data were developed by bandpass filtering the flaw response in the amplitude signal out of the rotary probe. The resultant flaw data illustrate excellent signal-to-noise responses to both the RFC target flaw size and a tight fatigue crack in Ti 6-2-4-6 material.

CONCLUSIONS

The experimental results presented in this paper demonstrate that the extremely high operating frequency of the active FMR eddy current probe does not limit it's effectiveness for crack detection in condi-

Fig. 10. Flat surface rotary probe operation.

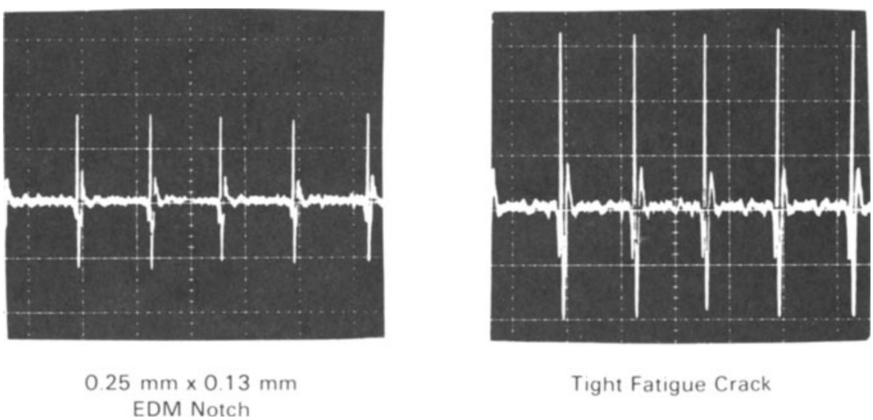

Fig. 11. Flat surface probe data.

tions of widely varying liftoff. We have also demonstrated that the active FMR probe and signal processor circuitry can be made practical, simple, and compact. In particular, we feel that one of the primary advantages of the active FMR probe over conventional coil probes is it's extremely small effective eddy current field diameter (or crack detection resolution) which is 0.38 mm utilizing a 0.30 mm YIG. This is important for sizing cracks in tight geometries. With the use of hybrid integrated circuit fabrication techniques, it should be possible to reduce the diameter of the small radius active FMR probe to inspect even tighter geometries such as 3.13 mm diameter cooling holes.

ACKNOWLEDGEMENTS

The author wishes to thank Mr. Mike Dodson for assistance in the mechanical design of the rotary probe and Mr. J. Mike King for his invaluable assistance in the fabrication of the active FMR probes, as well as the rotary probe signal processor.

FOOTNOTE AND REFERENCE

1. This work is being sponsored by the Air Force Wright Aeronautical Laboratories/Materials Laboratory under Contract No. F33615-82-C-5100 with Battelle, Pacific Northwest Laboratories.
2. J. M. Prince and B. A. Auld, "Development of Active Microwave Ferromagnetic Resonance Eddy Current Probes and Associated Signal Processing Methods," in Review of Progress in Quantitative Nondestructive Evaluation 3B, p. 1369 (1984).