WIRELESS EDDY CURRENT PROBE FOR ENGINE HEALTH MONITORING

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ABSTRACT. The first prototype wireless eddy current (EC) probe for on-wing inspection was demonstrated in a F100 PW-220 engine without external cabling at the Air National Guard overhaul facility in Des Moines Iowa. Wireless NDE probes have potential safety and economic benefits leading to prevention or mitigation of safety significant propulsion system malfunctions. Data from 2 MHz Eddy Current probes was transmitted using a dual-frequency, phase modulated wireless analog communication system. Notches down to 0.010" were detected by the system. This is comparable to the wired state-of-the-art EC technology currently used to inspect engines.

INTRODUCTION

Wireless eddy current (EC) probes couple EC inspection technology with wireless communication technology to allow the probe to be inserted in a jet engine and perform internal inspections without external cabling. Wireless NDE probes have potential safety and economic benefits leading to prevention or mitigation of safety significant propulsion system malfunctions. Conducting on-wing inspections requires getting the probe to the inspection location by "snaking" a probe through a guide tube or borescope port on the engine. During the inspection process, the probe requires uniform and controlled manipulation over the required inspection region. Wires for probe power and measurement signals can become tangled and/or break which complicates the inspection process.

The first prototype wireless eddy current (EC) probe for on-wing inspection was demonstrated in a F100 PW-220 engine without external cabling at the Air National Guard overhaul facility in Des Moines Iowa. Data from 2 MHz EC probes was transmitted by 2.4 and 5.7 GHz wireless communication links through the compressor and turbine stages attaining high resolution detection capabilities for 0.010" notches in a blade placed between the 2nd and 3rd compressor stages. This is comparable to wired, state-of-the-art EC technology used to inspect engines.

This paper discusses the major issues affecting system design, followed by the transmitter and receiver hardware design. The software explains the processing and display of the EC data. The results are compared to a wired EC tester. This paper concludes with summary and continuing efforts of this project.

SYSTEM DESIGN ISSUES

The major design considerations for the design of the wireless probe were low power, avoiding interference, reliable transmission, and linkage with the eddy current probe. Low power is necessary to have long battery life. The battery needs to have sufficient power to run both the EC probe and the wireless transmitter for the duration of an inspection.

Because a wireless probe should not interfere with other systems in the airport environment, interference between the wireless probe and other wireless systems was a key design issue. It is also important that other systems do not affect the performance of the wireless probe because vital information could be lost. To avoid interference with airport devices, the probe operates in the 2.4 and 5.7 GHz Industrial Scientific and Medical bands (ISM) [1]. The ISM bands are unlicensed bands that can be used for wireless signal transmission as long as Federal Communications Commission (FCC) specifications are met.

Reliable transmission requires that the signal be immune to multi-path fading. The communication channel, the medium through which the transmitted signal must travel, is the interior of a jet engine. Testing confirmed that the channel was a highly multi-path environment caused by the signal reflecting off of the fan blades. This type of multi-path environment leads to frequency selective fading. The test results indicated that a single carrier frequency could not be used throughout the entire engine. The phase modulation transmission method was selected to minimize the problem of fading and to simplify the transmitter design [2]. A frequency diversity transmission overcame the limitations of using a single carrier frequency. A frequency diversity transmitter sends the information on two separate carrier frequencies. From the results of engine testing, a carrier frequency was selected from the 2.4 and 5.7 GHz ISM bands. The frequencies selected provide complete interior coverage of the engine.

The eddy current probe used for this project is a 2 MHz differential probe. The hardware was designed to accommodate up to a 10 MHz signal, with filtering used to select the desired signal. Figure 1 shows a block diagram of the prototype wireless probe system. The receiver demodulated the radio frequency signal to recover the EC data. A PC-based data acquisition card digitized the signal at 5 MHz with a resolution of 12 bits. PC software estimated the 2 MHz reference signal from the EC probe and detected notches on a sample blade.

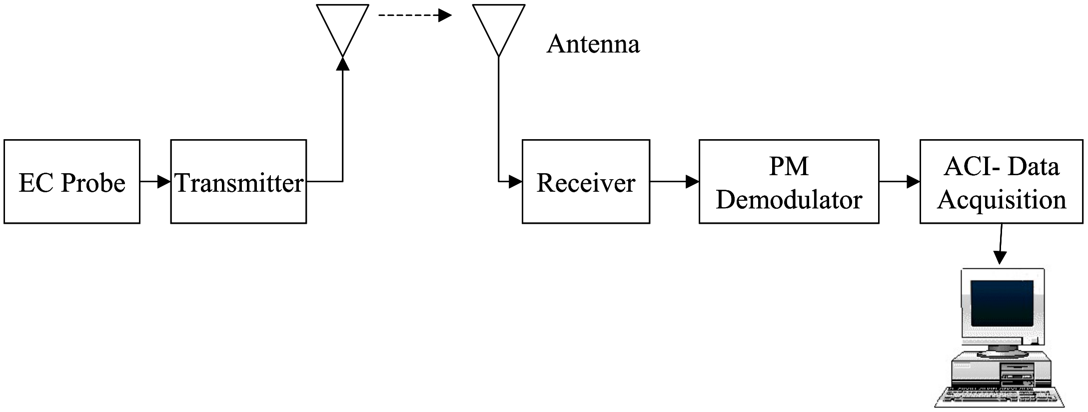


FIGURE 1. Block diagram of the prototype wireless EC probe system.

HARDWARE

The hardware consists of two separate but interlinked modules: the transmitter and receiver. The transmitter was designed to supply drive signal to the eddy current probe, modulate and transmit the reflected information to the receiver. The receiver was designed to recover the transmitted information and send it to the software for processing.

The prototype system was designed using a 2 MHz differential eddy current probe for fan blade inspections. A dual band frequency transmitter also known as a frequency diversity transmitter transmits the eddy current information in the 2.4 and 5.7 GHz Industrial Scientific and Medical bands (ISM) [1]. Dual channel frequency diversity allows the transmitted eddy current information to be transmitted in two separate frequency bands. This method increases the probability that the receiver will be able to recover the eddy current information by detecting a signal in one band or the other or in both bands. Testing verified that the most significant multi-path issue was frequency selective fading. Frequency selective fading occurs when a signal transmitted at a specific frequency experiences a sudden and significant loss of signal and cannot be recovered [3]. One way to combat this problem is to use a phase modulation scheme to transmit the eddy current probe data. Phase modulation is resistant to frequency selective fading and easy to implement in hardware.

Since the prototype used an analog communication system, only the reflected signal from the eddy current probe is transmitted. The cost in transmitted power to send the eddy current probe reference frequency was high, so the team made the design choice to estimate the probe reference signal directly from the reflected EC probe data.

Design of Transmitter and Probe Driver

A 2 MHz crystal oscillator supplies the drive signal to the eddy current probe. The driver amplitude is 800mVpp and resulted in a 20mVpp reflected signal. A 2-stage amplifier increases the signal that is then sent to the phase modulator. The increased amplitude of the reflected eddy current information provides a larger phase change in the phase modulator and makes the signal easier to detect. The 2 MHz eddy current information is then placed on an intermediate frequency of 824 MHz. The 824 MHz comes from a voltage-controlled oscillator (VCO) that creates the 2.4 and 5.7 GHz carriers. Once the eddy current information is placed on an 824 MHz carrier, it is then mixed with signals derived from the unmodulated 824 MHz signal resulting inthe carrier frequencies. The actual transmitter circuit has multiple amplifiers, doublers and microwave filters to achieve the 2.4 and 5.7 GHz carriers. A dual mode antenna then radiates the information across the wireless link. Figure 2 shows a block diagram of the transmitter design.

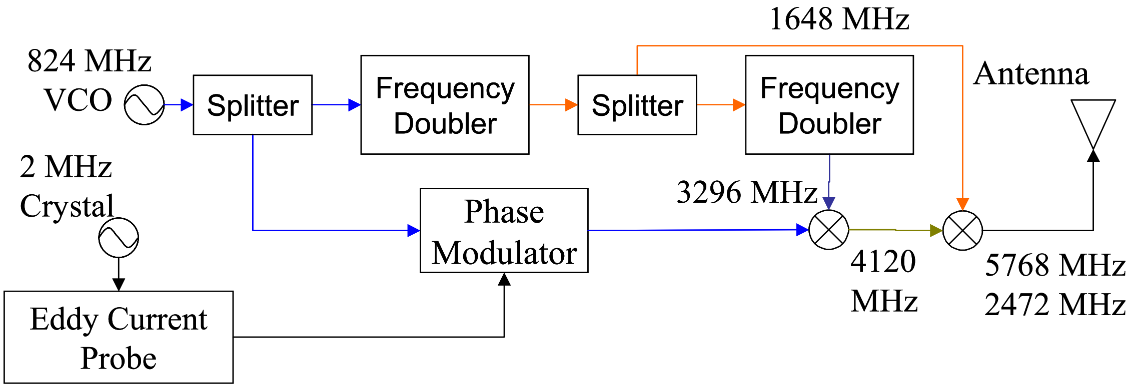


FIGURE 2. Block diagram of the dual-band phase-modulated transmitter.

Receiver Design

Figure 3 shows a block diagram of the receiver. The 2.4 and 5.7 GHz signals from the transmitter are received through a dual mode antenna and separated into their respective bands. The receiver consists of two individual phase locked loops (PLL) that lock onto the carrier frequency in each band. The 2.4 and 5.7 GHz signals are down converted to a lower frequency to simplify the PLL circuit. An automatic gain control circuit (AGC) has been added to each PLL loop to account for variable transmission loss. The AGC also ensures that the input to the PLL is kept at a constant power level to avoid damaging the integrated circuit. The PLL then extracts the phase-modulated information from the carrier. The phase-modulated information is the 2 MHz eddy current signal from the wireless probe. The eddy current signal is then filtered and sent to the computer for processing and displaying the eddy current response.

SOFTWARE

The software for the demodulation and display of the EC signal operates on a Windows-based PC. A data acquisition card digitizes the 2 MHz EC signal at 5 MHz with a resolution of 12 bits. The software processes and displays the EC signal.

Since the 2 MHZ probe reference signal is not sent across the wireless link, the software must estimate the reference before extracting the EC signal. The reference includes the frequency, magnitude, and phase from a designated starting point. Once the reference signal has been estimated, then the reflected data can be processed and displayed.

Estimating the reference signal was accomplished in a two-step process. The first step, a zero-crossing method, was used to provide a rough estimate of the frequency. This is accomplished by counting the number of zero crossings (from negative to positive zero crossings are only counted) over a prescribed number of samples. This result is then used by a software phase lock loop (PLL). The PLL compares the measured and estimated phase to adjust the reference frequency until a specified error tolerance is reached. Finally, the magnitude and phase are calculated using Goertzel's Algorithm [3].

After the reference has been calculated, the reflected signal can be processed to extract the I and Q components of the EC signal. The I and Q calculation was rotated (user defined) and low-pass filtered at a bandwidth of 100 Hz and additionally band-stop filtered at a level of 30 dB at 120 Hz. The I and Q results are then formatted and scaled for the display as shown in Figure 4. The display design was based on the Nortec NDT-19E tester. The display allows the user to adjust the rotation, scale, clear, and null the display.

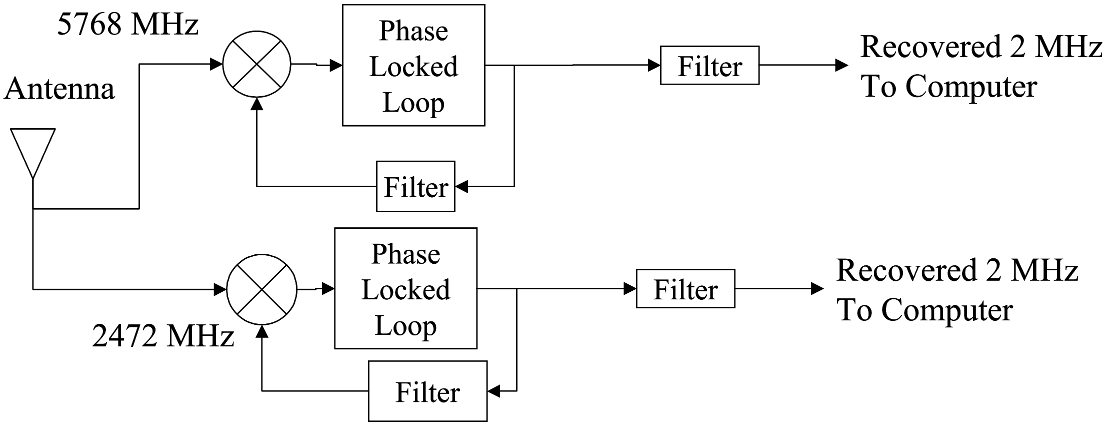
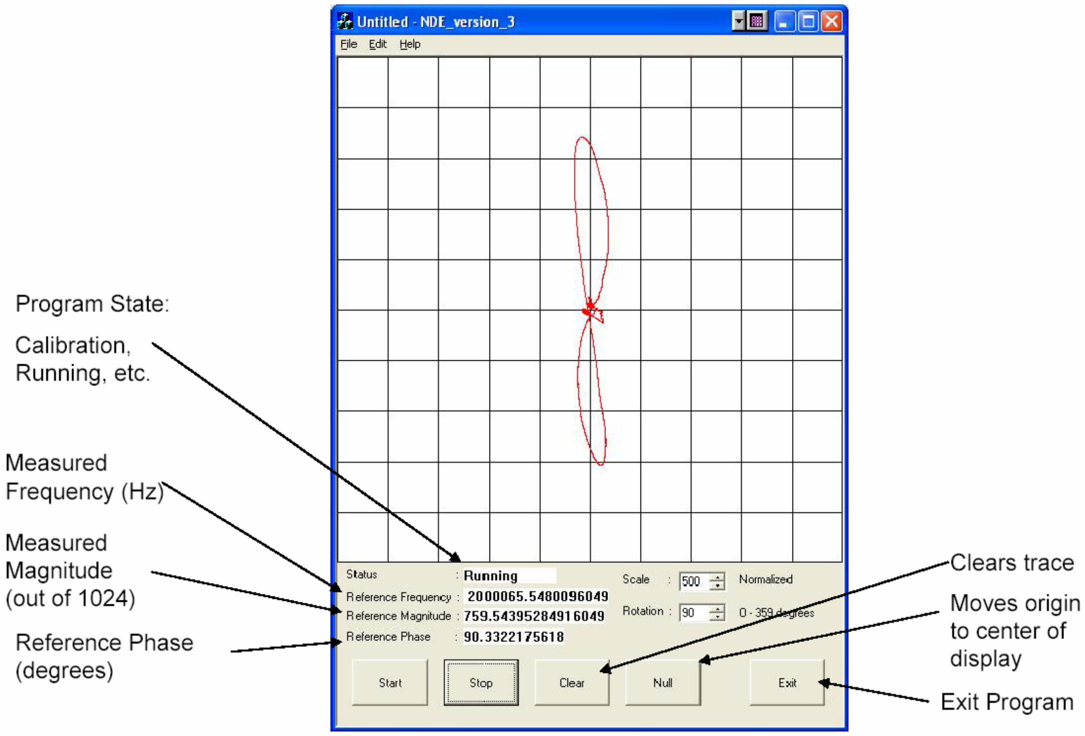


FIGURE 3. Block diagram of the receiver used for the wireless probe project



Status : Running
Reference Frequency : 2000065.5480096049
Reference Magnitude : 759.54395284916049
Reference Phase : 90.3322175618
Scale : 500 Normalized
Rotation : 90 0 - 359 degrees

Program State:
Calibration, Running, etc.
Measured Frequency (Hz)
Measured Magnitude (out of 1024)
Reference Phase (degrees)
Clears trace
Moves origin to center of display
Exit Program

FIGURE 4. Software display for the prototype wireless EC probe. Signal orientation and scaling are controllable by the user.

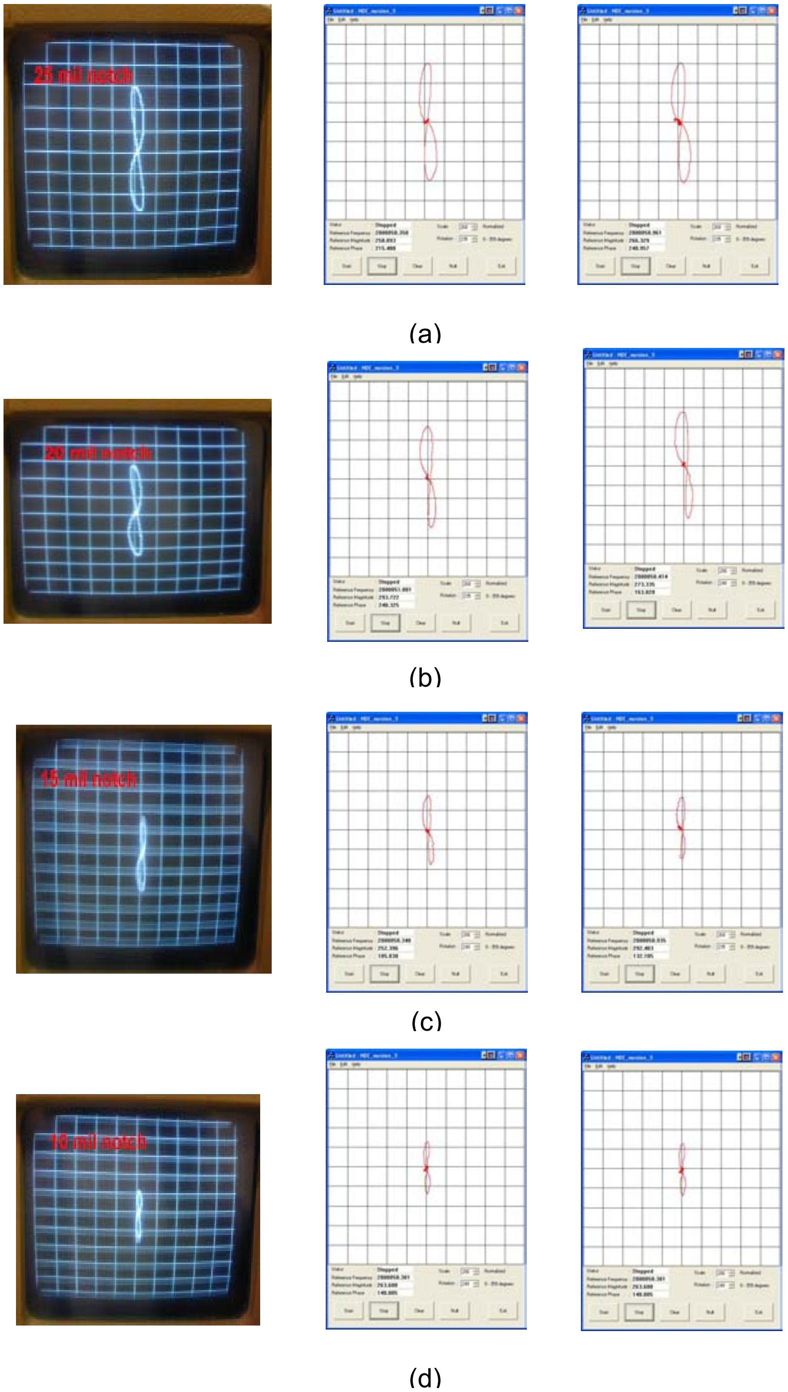
RESULTS

The testing was conducted at the Iowa Air National Guard in Des Moines, Iowa. The National Guard has a demonstration jet engine that was used to evaluate the wireless system. The same test samples were tested by the NDT-19E tester and the wireless NDE system. The NDT-19E parameters were: 2 MHz, ϕ= 190 °. The low-pass filters were set at 100 Hz. Both systems were calibrated using a 25 mil Electrical Discharge Machined (EDM) notch sample with the gain set to produce six divisions. Figure 5 shows the comparison between the NDT-19E tester and the 2.4 GHz data from the wireless system. The responses of both systems are nearly identical as a function of the positions of the transmitter and receive antenna in the test engine. The wireless system was operated with the transmitter located in the third stage of the low compressor and the receive antenna at the following positions:

- 6th stage – high compressor
- 12th stage – high compressor
- turbine
- engine inlet.

Figure 6 shows a comparison of the normalized peak signal value for different EDM notch sizes at the different test configurations for the 2.4 GHz wireless communication system. This figure illustrates the capability for wireless transmission of EC probe data through the compressor and turbine stages. This result demonstrates high resolution detection capabilities of .010” notches in a blade placed between the 2nd and 3rd compressor stages. This is comparable to wired and state-of-the-art EC technology used to inspect engines.

The same tests where conducted in the 5.7 GHz band producing nearly identical results between the third and sixth stages. The 5.7 GHz signal strength was insufficient to be detected by the receiver in the eleventh stage.



(a)

(b)

(c)

(d)

FIGURE 5. Comparisons between the NDT-19E and the wireless system using the same samples. The results are as follows: left column is from the NDT-19E, the middle column is between stage 3 and 6, and the right column is between stage 3 and 11. (a) Results from the 25 mil. sample (b) Results from the 20 mil. sample (c) Results from the 15 mil. sample (d) Results from the 10 mil. sample

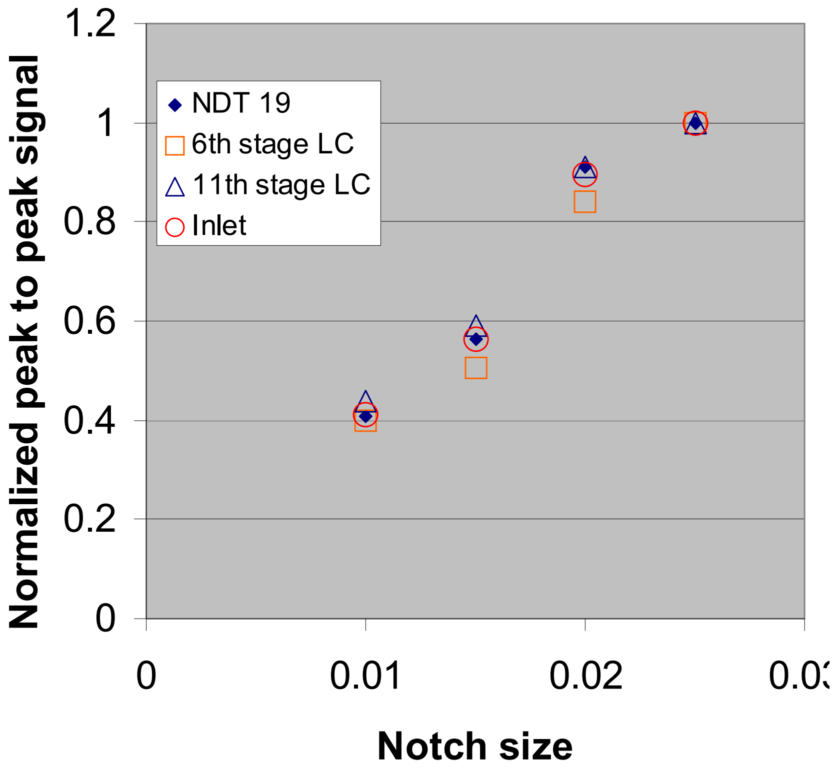


FIGURE 6. Comparison of the peak signal response between the NDT-19E wired EC probe and the wireless EC probe. The peak-to-peak signal sizes are normalized to the 0.025" EDM response. The wireless probe transmitter was located in the third stage of the low compressor. The receive antenna position was varied.

CONCLUSION

We have shown that wired eddy current probes can be converted to wireless probes. The prototype that was developed was an analog system. The next steps are to decrease power consumption and improve system signal-to-noise ratio by implementing a digital spread-spectrum communications system using an integrated circuit process

ACKNOWLEDGMENT

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