Developments in Near Electrical Resonance Signal Enhancement (NERSE) Eddy-Current Methods

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Abstract. In industry, the detection of small defects above a background noise threshold is always a limiting factor. This is true for even the most sensitivity and reliable of NDT techniques. However, defect signals in eddy-current (EC) inspections have the potential to be boosted above noise thresholds by exploiting the near electrical resonance signal enhancement (NERSE) phenomena, resulting from resonant frequency-shifting of an EC system as the coil passes over a defect. Following on from the observation and characterisation of this phenomenon, NERSE based EC methods are being investigated and developed for the detection of sub-millimeter surface defects in Aerospace superalloys. This paper discusses current advances in the development of such techniques and explores the potential of NERSE exploitation as well as examining its limitations.

Keywords: **Eddy-Current, Resonance, NERSE, Electromagnetic, coupling, NDT, NDE, defect detection.**

INTRODUCTION

Eddy-current testing (ECT) is widely used for many non-destructive testing (NDT) applications for its high sensitivity to small defects. However, the size of defect ECT techniques can detect has plateaued in recent years, and achieving high signal-to-noise ratios to sub-millimeter defects non-trivial. This issue is further compounded in the aerospace industry, by the use of complex geometry, failure critical components, made from low conductivity superalloys, whose properties make reliable detection of sub-millimeter defects significantly more difficult.

Low conductivity materials often require higher frequencies in order to achieve a suitable sensitivity to shallow defects as shallower skin depths create stronger interactions between the eddy currents and a surface defect[1]. Inspections of materials such as Titanium 6Al-4V (Ti6-4) and Waspaloy would ideally be operated between 5-10MHz in order to detect sub-millimeter defect. This is higher than the typical operation of conventional ECT systems[2] so eddy current measurements with these systems can suffer from higher electromagnetic noise at higher frequencies. The introduction of array probe technology adds further problems for sub-millimeter defect detection as coils within arrays are often much simpler and larger than their pen probe counterparts. They also have the added disadvantage of being unshielded and in close proximity to the other electromagnetic coils (inductors). All of this can have detrimental effects on their electrical measurements.

The near electrical resonance signal enhancement (NERSE) phenomenon[3, 4] has the potential to overcome some of these limitations for the detection and evaluation of sub-millimeter defects within these critical components. Research into the exploitation of the NERSE effect for defect detection was carried out, and potential operational methods based around an understanding of the NERSE effect are outlines.

THEORY

Eddy-current probes can be very simply approximated to a parallel LC circuit (FIGURE 1) where the eddy-current coil is represented by the inductor, L_0 [5]. The coaxial cable has capacitance, inductance and resistance, but at the frequencies of interest here is best represented by capacitor, C_0. The coil or inductive element also has an associated series resistance, R_0 and inter-turn capacitance, but at the frequencies discussed here inter-turn capacitance is neglected as it is insignificant when compared to the capacitance of the coaxial cable.

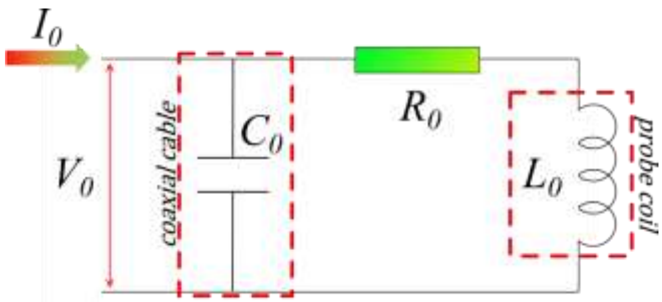

FIGURE 1. Circuit model: Simplified equivalent circuit for an eddy-current probe in free space with a coaxial cable connection.

This system will resonate at a specific excitation frequency where the impedance of the inductive arm and the capacitive arm are equivalent in magnitude, i.e. maximum impedance. The resonant frequency, f_0, of the system depicted in Figure 1 can be expressed as,

$$\omega_0 = 2\pi f_0 = \sqrt{\frac{1}{L_0 C_0}} \,. \tag{1}$$

When an eddy-current probe is brought into the proximity of an electrically conducting, non-ferrous, material, the simple circuit can be modified to express the change in electrical behavior. For an eddy-current system generating a plane wave magnetic field, the equivalence circuit can be expressed as a transformer circuit.

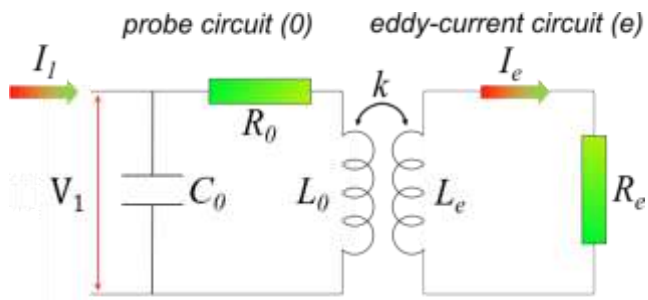

FIGURE 2. – Transformer circuit model of eddy-currents within the surface of a non-ferromagnetic material.

The resonant frequency of the coupled system, f_0', can then be expressed as,

$$\omega_0' = 2\pi f_0' = \sqrt{\frac{1}{C_0 L_0 \left(1 - \frac{k^2}{2}\right)}} \,, \tag{2}$$

Here, k is the coupling coefficient between the inductor probe and the surface of the material, and incorporates many physical variables including; separation, tilt, coil dimensions and inhomogeneity. However, it is also dependent on the condition of the material, including the presence of defects. Any change to the coupling coefficient will lead to a shift in the resonant frequency.

It has been shown in previous publications[3, 4] that this shift results in significant improvements in defect signal-to-noise ratios (SNR) at frequencies close to electrical resonance (**FIGURE 3**). This phenomenon, known as near electrical resonance signal enhancement (NERSE), has the potential to be developed and applied to many scenarios.

This paper outlines the initial steps in the development of NERSE based techniques for sub-millimeter defect detection in aerospace alloys.

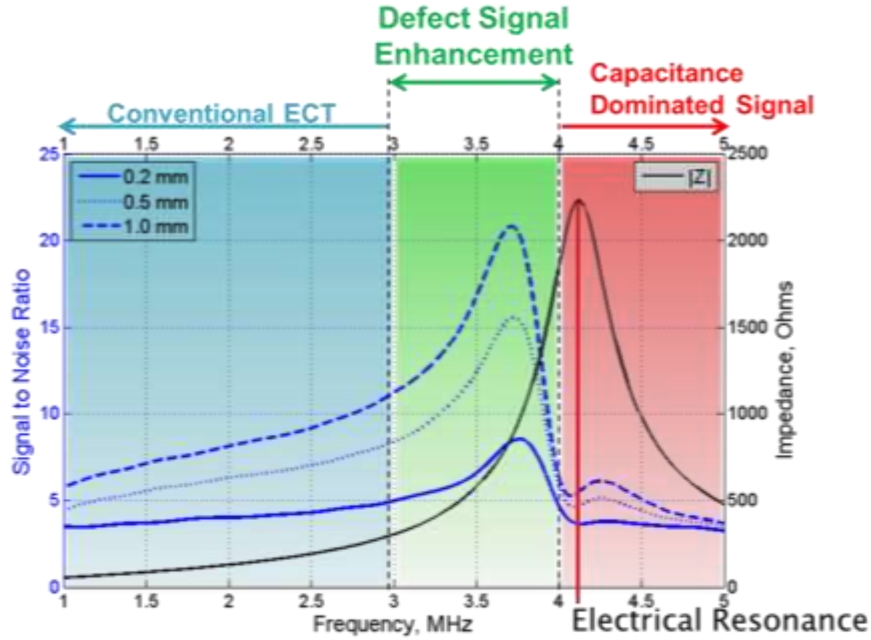

FIGURE 3 - Near Electrical Signal Enhancement (NERSE) calibration slot signals as a function of frequency of excitation shown in reference to the electrical resonant frequency[4].

NEAR ELECTRICAL RESONANCE SIGNAL ENHANCEMENT (NERSE) METHODS

The experimental apparatus for the NERSE system (**FIGURE 4**) comprises a Tektronix 3021B arbitrary function generator that generates an input voltage, V_{in}, which is converted, via an in-house Howland current source, into a stable, equivalent input current. The current supplies the eddy-current probe and the voltage across the probe, V_{out}, is recorded along with the input voltage, V_{in}. The ratio of the voltages is proportional to the impedance of the system.

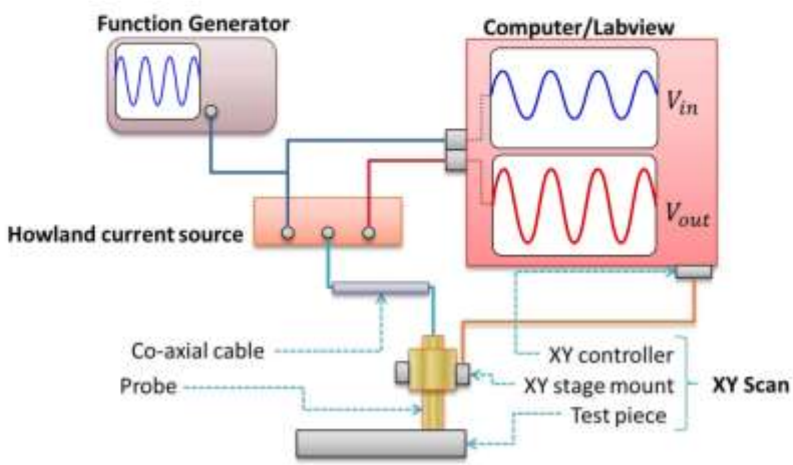

FIGURE 4 - Schematic diagram of the Near Electrical Resonance Signal Enhancement (NERSE) experimental apparatus.

The arbitrary function generator can be used to input a wide range of signals, therefore lending the system to experimental flexibility. Here we summarise preliminary investigations exploring potential methods for exploiting the effects of the NERSE phenomenon for defect detection in Aerospace superalloys. The approaches explored were; frequency sweeping, and single-frequency excitation.

Single Frequency Excitation

With an understanding of the NERSE frequency band[3] and it's potentially beneficial effects on defect sensitivity, the simplest exploitation of the effect would be to intelligently select a single frequency within this band in order to achieve a much greater signal-to-noise ratio (SNR) for sub-millimetre defects. This would push their signals above the traditional reject threshold of 3:1 SNR, thus achieving a greater inspection reliability and probability of detection.

Single frequency excitation opens the doors to averaging over a large number of cycles so as to reduce incoherent noise which will improve the signal enhancement effects of NERSE.

Three calibration slots of varying depth in a Titanium 6-4 calibration sample were inspected using discrete frequency sinusoidal excitation, averaging over 100 cycles. Multiple separate frequency scans were made and analyzed to demonstrate the relative improvements of the NERSE frequencies to conventional excitation frequencies. The frequencies used are shown in table 1 along with their cycle period.

Table 1 - Single frequency measurement speed compared to sweep measurement

	Frequency (MHz)	**1 cycle period (μs)**	**100 cycle period (μs)**
Single Frequency	1.0	1.00	100.0
	2.5	0.40	40.0
	3.0	0.33	33.3
	3.6	0.28	27.8
	3.8	0.26	26.3
	4.0	0.25	25.0
	5.0	0.20	20.0

	Frequency (Hz)	**1 sweep period (μs)**
Sweep	1923	520

Single frequency excitation offers improved measurement speed compared to sweeping. The speeds are not so important for single coil inspections, however, the integration of NERSE methods into eddy-current array technology will require very rapid measurements in order to achieve industrially viable scanning speeds.

Frequency Sweep Excitation

Frequency sweeping can be used to obtain much greater detail on defects. By analyzing the measured frequency spectrum of the sweep, defect specific features can be recognized and considered.

An input voltage was constructed to sweep through a range of frequencies, from *2.5-5 MHz*, in *0.52 ms*. The signal was wrapped in an exponentially decaying envelope function in order to counteract the linear increase in the inductance of the system with frequency. Without this feature the scale of the V_{out} measurement system would quickly saturate with increasing frequency. With this feature, V_{out} maintains an even screen height of between 60-80%, thereby achieving a good dynamic range across all frequencies.

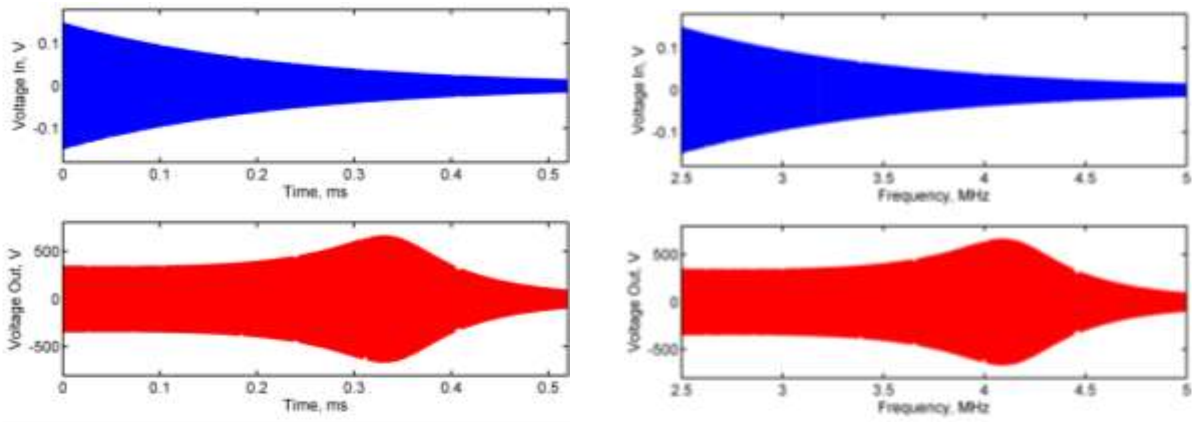

FIGURE 5 – Typical Voltage In and Voltage Out time and frequency trace signals from a *2.5-5.0 MHz*, exponentially decreasing frequency sweep for an example probe resonating at *4.1 MHz*.

This method was used to scan a Waspaloy alloy material containing 4 sub-millimetre surface EDM notches of dimensions stated in table 2.

Table 2 - Waspaloy sub-millimeter EDM notch dimensions

Notch #	**A**	**B**	**C**	**D**
Length (mm)	0.27	0.39	0.54	0.68
Depth (mm)	0.15	0.22	0.29	0.28
Gape (mm)	0.10	0.10	0.10	0.10

ECT Probe

Both NERSE methods were applied to a single, high frequency, ferrite cored and capped, coil pen probe. A schematic diagram of the probes cross-sectional dimensions is shown in figure 6.

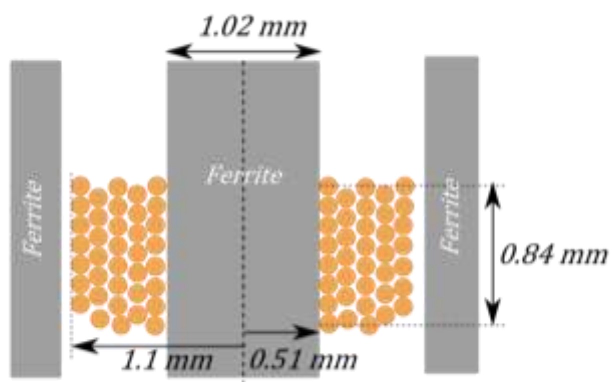

FIGURE 6 - Eddy-current probe coil: cross-sectional schematic diagram of ferrite cored and capped coil.

RESULTS

Single Frequency Excitation

A scan of three calibration slots in Titanium 6-4 was performed using seven discrete sinusoidal excitation frequencies, averaged over 100 cycles. The defect SNR results are compared along the frequency axis in figure 7.

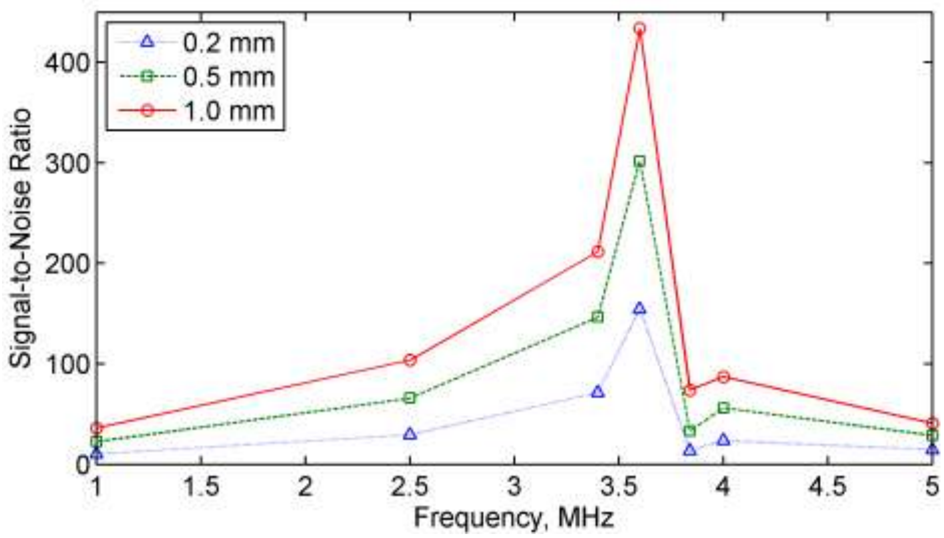

FIGURE 7 - Single frequency excitation showing the significant signal-to-noise improvements achievable in the NERSE frequency range for three different depth calibration slots in Ti6-4.

The results exhibit the same general trend, as a function of frequency, as the frequency sweep results of figure 3[3]. The enhancement effects of the NERSE phenomenon are even more pronounced once averaging has reduced the level of incoherent noise in the measurement. Table 3 summarises the SNR enhancement observed using single frequency excitation.

Table 3 - Signal-to-Noise (SNR) of each frequency to the three calibration slot depths both un-normalised and normalized to the 1MHz SNR result.

	Un-Normalised			**Normalised to 1MHz**		
	SNR to Slot Depth (mm)			SNR to Slot Depth (mm)		
Freq. (MHz)	0.2	0.5	1	0.2	0.5	1
1	10.45	22.56	36.14	1.00	1.00	1.00
2.5	29.58	65.86	103.6	2.83	2.92	2.87
3.4	71.3	146.7	211.6	6.82	6.50	5.86
3.6 *(NERSE)*	**154.4**	**301.7**	**434.2**	**14.78**	**13.37**	**12.01**
3.8	13.55	33.09	3.84	1.30	1.47	0.11
4	23.54	56.09	87.32	2.25	2.49	2.42
5	14.75	28.73	40.82	1.41	1.27	1.13

Table 3 identifies that the measurement at the NERSE frequency has the greatest enhancement effect, relative to the equivalent measurement at 1MHz, on the smallest slot depth.

Frequency Sweep Excitation

Four sub-millimetre EDM notches in Waspaloy were scanned using the frequency sweeping method, sweeping from 2.5-5MHz. The resonant frequency of the system, coupled to the surface of undamaged Waspaloy, is 4.1MHz. The frequency spectra of the four defect signals are displayed in figure 8 relative to the impedance magnitude profile, $|Z|$, of the system on undamaged Waspaloy.

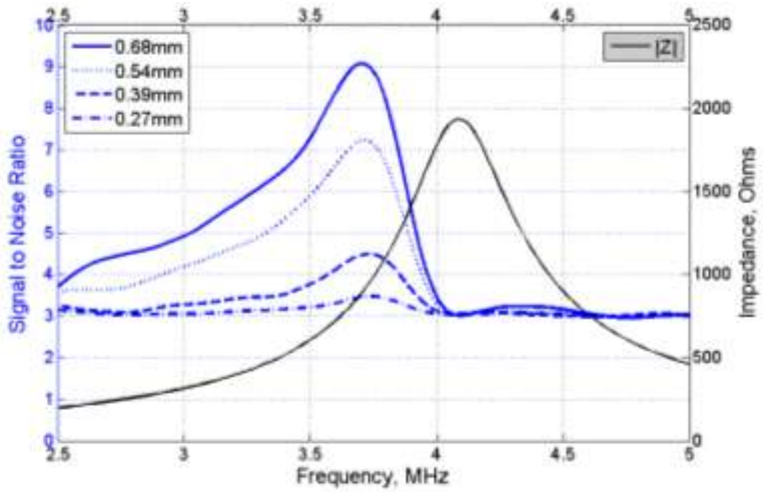

FIGURE 8 - SNR plots for four EDM notches over a range of frequencies passing through electrical resonance. Results are compared to the magnitude of impedance (black solid). Plot separated into three frequency bands; conventional, defect enhancing and capacitance dominated.

The results indicate that a changing notch size produces different levels of resonance shifting, so that the peak NERSE frequency is different for each defect.

Table 4 – Summary of NERSE enhancement effects on sub-millimeter EDM notches in Waspaloy relative to 2.5MHz result.

Defect length (mm)	SNR at 2.5 MHz	SNR at (3.75MHz) NERSE Peak	NERSE Enhancement from 2.5 MHz
0.27	3.15	3.48	1.10
0.39	3.25	4.49	1.38
0.54	3.57	7.24	2.03
0.68	3.71	9.08	2.45

Defects smaller than the coil thickness, *0.5mm* (outer radius minus inner radius), have a significantly reduced influence on the resonance shift of the system. This significant observation confirms that the minimum defect size capable of being detected by any given coil is dependent on the dimensions of the coil. This will factor into the design of future NERSE operation probes.

CONCLUSIONS

Exploitation of the near electrical resonance signal enhancement (NERSE) phenomenon for sub-millimeter defect detection and evaluation has been investigated. Single frequency and frequency sweeping excitation methods were examined to investigate their potential as NERSE based techniques.

Single sinusoidal frequency excitation was explored as the simplest exploitation of the NERSE phenomenon. Intelligently selecting the frequency, based on the resonant frequency of the system, and averaging over a number of cycles, allows the system to benefit from the resonance shifting enhancement effect and reduces incoherent noise respectively. It was shown that the enhancement effect appears to have a greater effect on smaller defects relative to measurements of the same defect at conventional frequencies. Future work will investigate this more closely to determine its validity and investigate single NERSE frequency measurements on sub-millimeter defects so as to push smaller defect signals above the typical decision threshold of 3:1 SNR.

Frequency sweeping excitation was also examined as a method of obtaining a much larger amount of information on the system and on the relative size of discontinuities, however, the sweeping approach is a relatively time consuming technique that does not lend itself easily to the simple pass-or-reject type of inspection frequently carried out in industry.

NERSE operation can be affected by liftoff, tilt, sample inhomogeneity, electrical anisotropy or geometric effects which can produce similar shifts in the resonant frequency of the system as a defect. This could potentially lead to false indications or the shifting of the resonant frequency such that a single excitation frequency is no longer at the most sensitive NERSE frequency. For this reason the single frequency approach is being developed as a technique for controlled scanning systems (i.e. robotic control) so that such effects can be minimized or welldefined. The results in this study were obtained on samples cut from real industrial components and measurements were made using comparable robotic manipulation to that commonly used in industry.

For inspections interested in the evaluation of a defect, where the speed is less significant, frequency sweeping could be used. With a frequency sweeping technique, liftoff effects can be monitored and the whole spectrum assessed to provide more information. Frequency sweeping excitation could be made faster by exciting the frequencies in specifically designed pulses. This avenue of research will be investigated in future work.

ACKNOWLEDGMENTS

The authors would like to acknowledge Rolls-Royce plc. and the Research Centre for Non-Destructive Evaluation (RCNDE) for their support, funding and encouragement.

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