Defence R&D Canada
External Literature
DRDC-RDDC-2015-N093
March 2015

Application of Alternating Current Field Measurement for Determination of Surface Cracks and Welds in Steel Structures at Lift-off

Shannon P. Farrell[1], Martin Lugg[2], and Kyle Avery[1]
[1]Defence Research & Development Canada
Dartmouth, NS, Canada
(902) 427 3437; fax (902) 427 3435; e-mail shannon.farrell@drdc-rddc.gc.ca

[2]TSC Inspection Systems,
Milton Keynes, UK
+44 1908 317444; fax +44 1908 290959; e-mail mlugg@tscis.com

ABSTRACT

Alternating Current Field Measurement (ACFM) is a novel technique for Non-destructive inspection (NDI) and sizing of surface breaking cracks on conductive surfaces. This document examines the precision and accuracy of the ACFM technique for inspection of simulated surface breaking geometrical defects (ex., cracks) and electromagnetic discontinuities (i.e., welding, excessive grinding or corrosion) in high strength, low permeability steel plates at lift-offs ≤ 30 mm. An off-the-shelf standard array probe was shown to be effective at measuring crack lengths with an accuracy of ± 6% and a precision of ≤ 4 % at 0 and 4.4 mm lift-offs. The specialized high lift-off probe exhibited a precision of ≤ 5 % and an accuracy that decreased with increase in lift-off from ± 5% (at 0 lift-off) to ± 9 % (at 19.4 mm lift-off). The high lift-off probe was capable of detecting and sizing welding at 30 mm lift-off. Investigations are underway to improve the accuracy of the high lift-off probe to quantify depth.

INTRODUCTION

The morphology and distribution of surface discontinuities (ex., defects and corrosion wastage) is a key component of structural integrity assessments and damage tolerance analysis of naval structures. The capacity to inspect at lift-off, through coatings, offers a tangible reduction to inspection resources and return-to-service timelines over similar traditional approaches (ex., magnetic particle, liquid penetrant). Other potential benefits include the capacity to increase the scope and frequency of inspections and improve the probability of detection while enabling quantitative crack monitoring over time. This, together with preventative maintenance has the potential to improve operational safety and performance of naval platforms.

Several NDI approaches were examined for their capacity to detect and measure small scale discontinuities (ex., cracking, corrosion wastage) and microstructural/metallurgical variation (associated with welds) steel surfaces at up to 30 mm lift-off. This paper summarizes efforts to evaluate a standard and specialized ‘Amigo’ ACFM probes to detect and size surface breaking cracking in high strength, low permeability steel at various lift-offs. Given its similarity to Eddy Current testing, ACFM was also investigated for its sensitivity to electromagnetic discontinuities.

BACKGROUND TO ACFM

ACFM is an electromagnetic technique developed for use in the offshore oil and gas industry to inspect welds on jacket structures, pressure vessels, piping and drill treads and risers [1]. Commercial systems also offer a variety of probes for inspection at 1 mm or 5 mm lift-offs that would enable detection under paint, corrosion products and insulation. This enables crack inspections without extensive preparation and removal of over layers

The ACFM technique employs probes with magnetic field induction coils to induce a uniform high frequency (5-50 kHz) alternating electric current (i.e., Eddy currents) in the outermost surface of a conductive material. Although similar to Eddy Current testing, it does not use a compact circular excitation current and is less prone to lift-off and material property changes [1]. While designed and employed to find surface discontinuities (cracks), magnetic field perturbations are also expected to be sensitive to changes in material properties – similar to Eddy Current methods.

Figure 1 is schematic showing how the ACFM technology works. While the magnetic fields induce Eddy currents (red lines) within the surface of the material, flowing current also induces a magnetic field above the surface.

Surface breaking defects that disturb the flow of the electric current within the surface, will also perturbate the magnetic field at the surface plane as well as across the bottom of the crack. Sensors in the ACFM probe measure the magnetic field (B) perturbations in up to three orthogonal (x, y and z) directions [2].

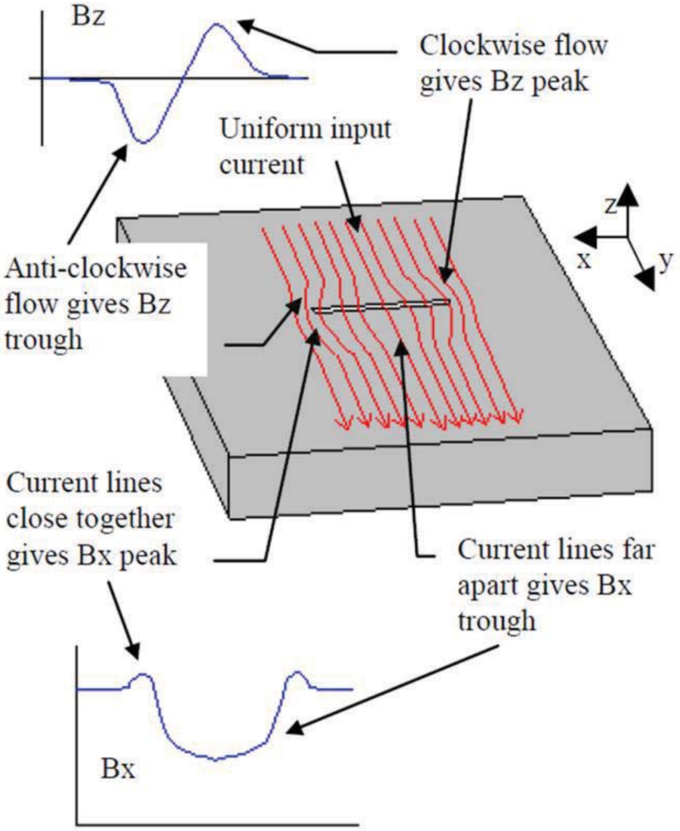

Figure 1: Schematic showing how the induced current (red lines) flows around a defect and how the data (blue) collected by the probe sensor [2].

The magnitudes of the perturbations are proportional to the electrical disturbance and the size of the defect. Software algorithms are then used to interrogate the directional magnetic field perturbations (Bx, By and/or Bz) to locate surface breaking cracking and determine the depth (from Bx or By) and length (from Bz) of the crack within minutes. Probability of detection may be improved when Bx and Bz signals are plotted against each other in a closed loop indication (the Butterfly plot) that identifies the presence of a crack. This Butterfly plot is not sensitive to probe speeds and confirms that the entire crack width is interrogated during a scan [2]. Standard practice for use of ACFM techniques for examination of weld for cracking is described in ASTM E2261-07 [3].

The standard ACFM ‘Amigo’ Type 275 flat bottom array probe has a 24 sensor (8Bx, 8By, 8Bz) array and was designed to operate at < 10 mm lift-off. The array probe has an optical encoder to provide position feedback during use and scan speeds up to 15 mm/sec. This together with an array width of >50 mm suggests that the instrument is capable of scanning a 1m^2 region in 20 minutes – considerably faster than techniques requiring surface preparation.

Standard ACFM probes that operate at 5 kHz were not designed to inspect through coatings thicker than 10 mm. Limitations reflect the effect that lift-off from a steel surface has on the outgoing and incoming signals. Previous investigations into ACFM inspection through coatings have shown that standard probes can still detect a 50 mm by 5 mm deep defect through 20 mm of coating thickness; however the signal is weak and difficult to interpret.

DRDC contracted TSC to develop a specialized 16 sensor (8Bx, 8Bz) array that employs a new magnetic field inducer (5 kHz) and differentially wound sensor coils to detect a 25 mm long x 4 mm deep simulated crack in high strength, low permeability steel at 30 mm lift-off. Results from experiments are described in succeeding Sections.

INSPECTION AT LIFT-OFF

Calibration is key for accurate inspection of high strength, low magnetic permeability steels. Previous studies had indicated that at 30mm lift-off, magnetic field edge effects pervade the materials up to ~ 200 mm from each edge – significantly reduces the reproducibility of data collected at lift-off. Therefore, large 600 mm x 600 mm plates were fabricated with cracks near the center of both sides. An Electric Discharge Machine die sinker was selected to address the need to create a narrow width, deep crack feature as well as minimize any internal residual stress. Crack lengths and depths are reported in Table 1.

Table 1: Results of employing the specialized array probe for detection of simulated cracking at various lift-offs from steel plates. Probe design was more sensitive at 10 mm lift-off and less sensitive at 30 mm.

HY80 crack dimensions (mm)					0mm lift-off			10.4mm lift-off			19.4mm lift-off			30mm lift-off		
Design		Vernier measure			Lenth (mm)			Lenth (mm)			Lenth (mm)			Lenth (mm)		
Length	Depth	Length	Depth	Width	Average	Precision	Accuracy	Average	Precision	Accuracy	Average	Precision	Accuracy	Average	Precision	Accuracy
100	8	101.2	8.0	0.69	100	3	-2	99	2	-3	96	1	-5	93	3	-8
100	6	101.0	6.0	0.71	103	3	2	98	1	-3	96	3	-5	102	2	1
100	4	101.2	4.0	0.71	105	2	3	99	3	-2	101	2	0	98	1	-3
100	2	101.2	2.0	0.74	105	2	3	105	2	4	109	4	8	110	4	8
50	8	51.1	8.0	0.68	49	0	-4	49	2	-5	48	1	-6	47	2	-7
50	6	51.1	6.0	0.70	54	5	5	47	2	-7	51	3	-1	55	3	7
50	4	51.0	4.0	0.70	51	3	1	50	2	-3	47	1	-9	49	3	-3
50	2	51.1	2.0	0.67	49	1	-4	51	2	-1	54	0	6	64	3	~

Standard Array Probe. Standard ACFM approaches were used to determine the precision and accuracy of the standard array probe at 0 and 4.4 mm lift-offs. To reduce operator bias, a different sensor was positioned over the crack location and was used for sizing. Software results indicated that the standard probe could determine crack lengths with an accuracy of ± 6% and a precision of ≤ 4 %. While depths had a precision of < 1 %, they were undersized by ~70%. The software algorithm would not size at > 4.9 mm lift-off. This suggested that the technique was sensitive, but calibration or a software modification is required to improve the accuracy of depth measurements.

Visual examination of the Bx signals suggested a correlation between crack depth and crack signal maxima. Figure 2 shows a graph of the difference between average Bx maxima and minima (for the sensor over the crack) against crack depth (measured with Vernier). Error bars reflect overall precision of measurement as determined using the square root of sum of squares method. A linear regression through all data points at each lift-off provides an algebraic expression that allows the calculation of the depth from the Bx maxima and minima.

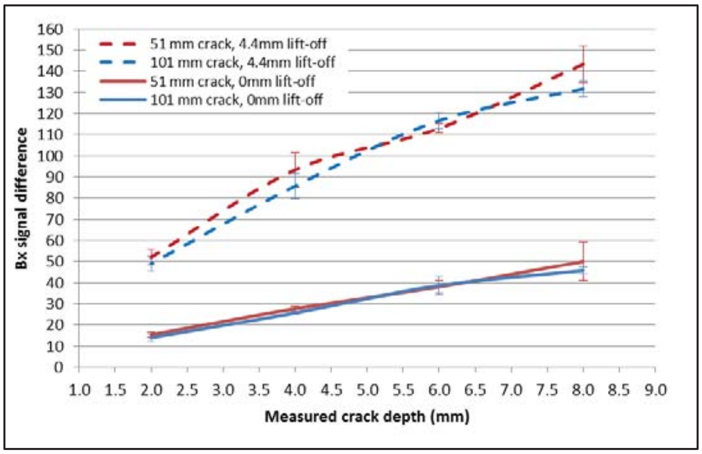

Figure 2: Standard array probe at 0 (solid lines) and 4.4 mm lift-off (dashed line).

Specialized Array Probe. The approach for using the specialized array probe was similar to the standard probe, except that it used lift-offs of 0, 10.4, 19,4 and 30 mm. Results are shown in Table 1. The precision for the measured crack lengths was relatively constant at ≤ 5 %. The accuracy decreased with increase in lift-off from ± 5%

at 0 lift-off to ± 9 % at 19.4 mm lift-off. The software did not contain an algorithm for calculation of crack depths using the data from the specialized array probe.

Similar to the standard array probe, the difference between average Bx maxima and minima were graphed against crack depth (Figure 3). The linearity in the data at each lift-off provides a means to calculate the depth of real cracks through examination of the Bx signal. The specialized array probe was design to be more sensitive at 10 mm lift-off and less sensitive at 30 mm.

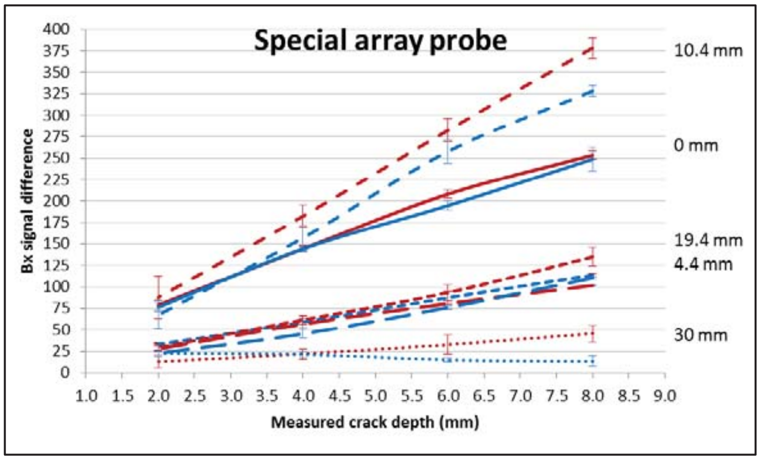

Figure 3: Specialized array probe at various lift-offs.

Weld regions at lift-off. ACFM was used to measure the surface extent and depth of weld overlay patches for two weld repaired steel plates. The weld patches were ground flat. The extent of the weld patches are described in Table 2. While preliminary, the ACFM measurements were in good agreement with what was expected and were found to demarcate the lateral extent of the weld overlay regions. One notable exception was the medium patch. This patch was expected to be 3 mm deep, while ACFM indicated a depth 5.9 ± 0.3 mm.

Given that eddy currents shouldn't penetrate far enough into the steel to permit depth analysis, the Bx signal could be related to the surface permeability changes related to a thicker weld. While promising, a more thorough analysis of the data and calibration of the sensors is required. TSC is developing new software to enable more accurate measurements at depth.

Table 2: ACFM measurements to detect weld overlay in steel plates at lift-off.

Weld overlay standard specifications				ACFM Measurements (mm)			
Specimen	Directions	Patch dimensions (mm)		1 mm liftoff		25 mm liftoff	
		Design	Measured	Avg	Std	Avg	Std
Small patch	∥ weld passes	100	110	111	2	101	1
	⊥ weld passes	100	107	107	3	99	5
	depth	3	?	3.1	0.5	requires calibration	
Medium patch	∥ weld passes	200	206	203	2	199	2
	⊥ weld passes	200	203	199	1	196	4
	depth	3	?	5.9	0.3	requires calibration	
Large patch	∥ weld passes	300	305	302	2	285	6
	depth	3.2	3.5	3.5	0.5	requires calibration	
Comments: Standard array probe used for 1mm lift-off, while specialized array probe used for 25 mm liftoff. The largest signals were used for depth/length analysis.							

While unexpected, the fluctuations in Bx and Bz signals response as the probe moves perpendicular to the weld passes suggests that the specialized probe is sensitive enough to discern multiple weld passes (Figure 4). This was less pronounced with increase in lift-off distance.

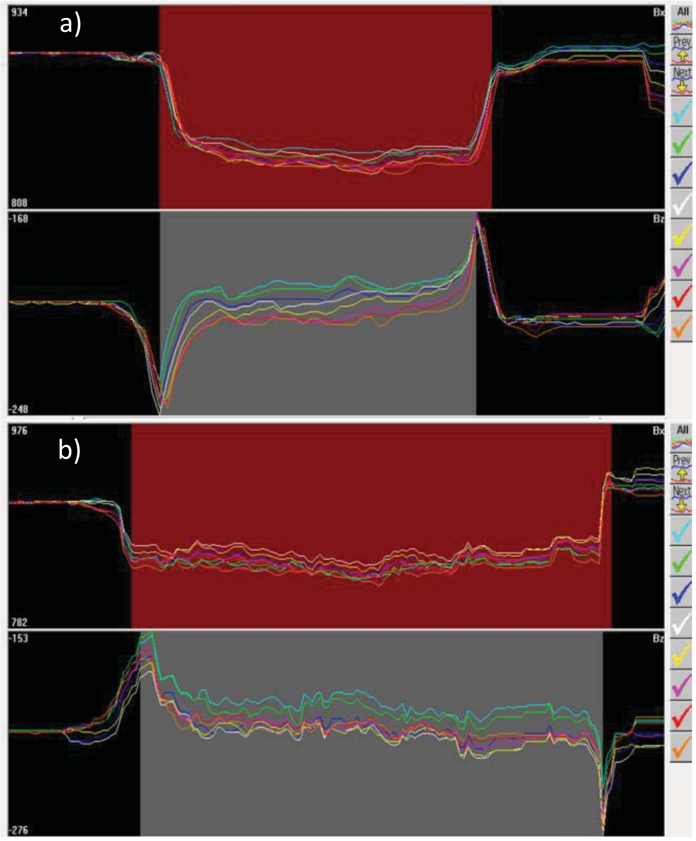

Figure 4: Standard array probe at 1 mm lift-off (a) parallel and (b) perpendicular to weld passes. Bx (top) and Bz (bottom) signals were used to determine depth and length of weld overlay, respectively.

During a field trial on a Canadian naval platform, the ACFM was also successfully demonstrated to locate weld overlay repairs and weld seams at high lift-off. This allowed for mapping the lateral extent and depth of weld regions without removal of surface over-layers.

SUMMARY

ACFM has been shown to be effective for inspection of simulated surface breaking geometrical defects (ex., cracks) and electromagnetic discontinuities (- either welding or excessive grinding) in high strength, low permeability steel plates at lift-offs ≤ 30 mm. An off-the-shelf standard array probe was shown to be effective at measuring crack lengths with an accuracy of ± 6% and a precision of ≤ 4 % at 0 and 4.4 mm lift-offs. The specialized high lift-off probe exhibited a precision of ≤ 5 % and an accuracy that decreased with increase in lift-off from ± 5% (at 0 lift-off) to ± 9 % (at 19.4 mm lift-off). The high lift-off probe was capable of detecting and sizing welding at 30 mm lift-off. Further investigations are underway to improve the accuracy of the high lift-off probe to quantify depth.

References

1. Topp, D. “Recent Developments and Applications of the ACFM Inspection Method and ACSM Stress Measurement Method”, *Proceedings of the 9th European Conference on NDT*, Berlin, 2006.
2. Lewis, A.M., D.H. Michael, M.C. Lugg and R. Collins “Thin-skin electromagnetic fields around surface breaking cracks in metals” *J. Appl.Phys*. 64(8), pp 3777-3784, 1988.
3. “Standard practice for examination of welds using the Alternating Current Field Measurement Technique”, *American Society for Testing and Materials*, ASTM E2261-07, 2007.