ENHANCED DEFECT CONTRAST USING VORTEX CROSS-CORRELATION IN MULTI-DIRECTIONAL EDDY CURRENT LOCK-IN THERMOGRAPHY

MEMBER OF BASQUE RESEARCH & TECHNOLOGY ALLIANCE

Angel Cifuentes*, Edurne Jaime-Barquero, Eider Gorostegi-Colinas and Ander Muniategui

LORTEK, Basque Research and Technology Alliance (BRTA), Ordizia (Gipuzkoa), Spain

ABSTRACT

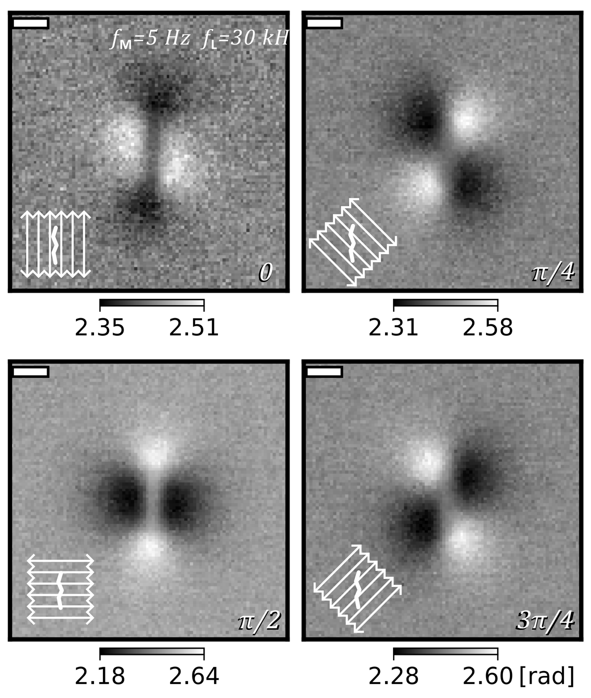
Eddy Current Thermography (ECT) is an effective and highly automatable technique for detecting surface-breaking cracks, offering improved detectability compared to conventional methods such as fluorescent magnetic particle or penetrant liquid inspection. This makes it particularly attractive for modern industrial quality assurance. Its full potential is realized when combined with frequency-resolved analysis methods, such as lock-in amplification or Fourier analysis, which reveal characteristic phase patterns in the thermal response. Short cracks typically generate a distinctive multilobed "butterfly" pattern, enabling reliable detection and localization. The orientation of these lobes correlates with the crack direction, providing intuitive insight into defect geometry. These inherent, structured patterns also make ECT especially well suited for AI-based automatic inspection.

I. INTRODUCTION

Active infrared thermography (AIT) has been proven to be a valuable non-destructive testing (NDT)[1] in the past decades due to its high degree of automatability. This work is centred on Eddy current thermography (ECT), where an inductor is used to generate Eddy currents in an electrically conducting sample. The currents result in abnormal heating in faulty region making the defect detectable. ECT is often seen as a potential replacement for fluorescent magnetic particles and penetrant dye inspection, where defects are generally surface-breaking cracks [2,3].

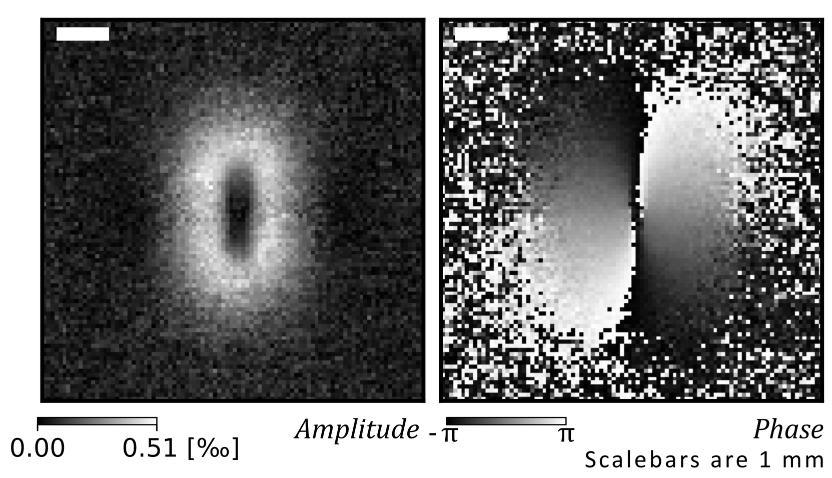
II. MULTIDIRECTIONAL-ECT

We utilize a frequency resolved ECT technique, where the induction current with a frequency f_L is amplitude modulated at a frequency f_M and via a FFT we retrieve the response of the sample. We then extract the phase image $\boldsymbol{\Phi}$ which exhibits a characteristic multi-lobed, or butterfly, pattern (MLP) when short cracks are present. To improve defect detectability we use multiple current directions, a method known as multidirectional ECT (M-ECT)[4] using four different current directions ($\theta = 0, \pi/4, \pi/2, 3\pi/4$). On the right the results of an M-ECT measurment on a 1 mm long notch on inconel 718 can be seen.



We then combine the four phase images of each direction through a complex weighted sum in a similar fashion to Phase Shifting in optics(PS):

$$I = \sum_{\theta=0,\frac{\pi}{4},\frac{\pi}{2},\frac{3\pi}{4}} \exp[i\Phi_\theta]\cdot e^{i2\theta}$$



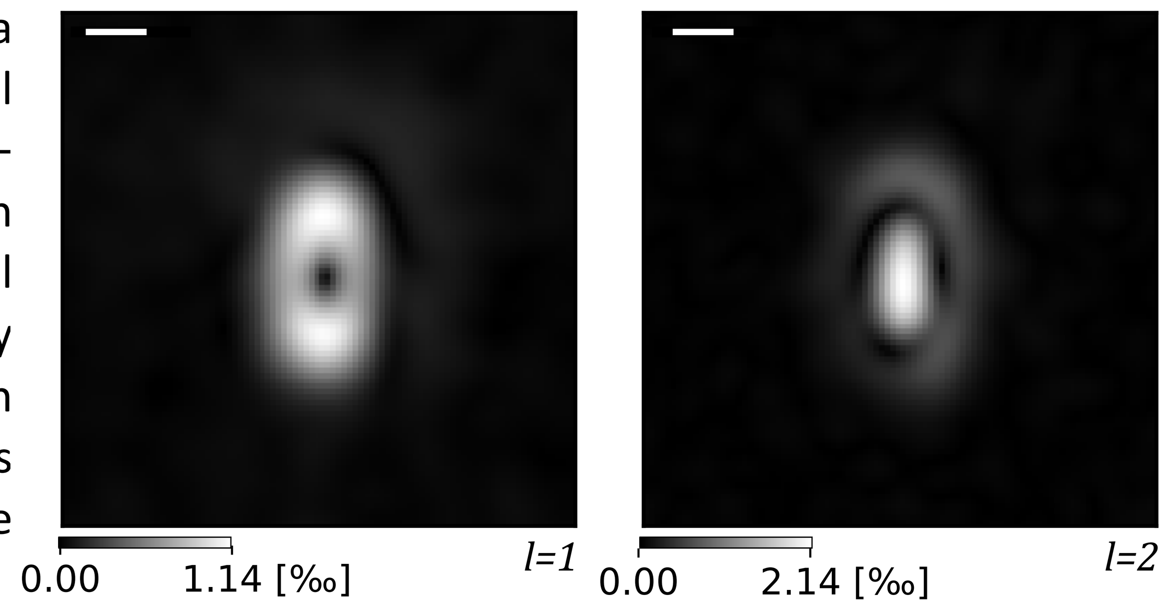
III. VORTEX CROSS-CORRELATION

$$\Lambda_{l,p}(r,\phi) = \frac{C_{p,l}}{w_0}\left(\frac{\sqrt{2}\,r}{w_0}\right)^{|l|} L_p^{|l|}\left(\frac{2r^2}{w_0^2}\right) e^{-r^2/w_0^2 + il\phi}$$

$\Lambda_{l,p}(r,\phi)$: LG mode (z=0)
$L_p^{|l|}$: Laguerre polynomial
$\frac{C_{p,l}}{w_0}$: normalization
$p=0$: no radial structure

$w_0 = \mu$: waist
$\mu = \sqrt{\alpha/(\pi f_M)}$: thermal diffusion length
α: thermal diffusivity
f_M: modulation frequency

In the previous section, a vortex is observed, with the phase wrapping around a singularity around the notch. A practical way to identify vortices is to cross-correlate the field with a vortex-carrying orthogonal basis, such as Laguerre–Gaussian (LG) modes [5]. Each mode is defined by a radial index p(number of intensity rings, in this case *p=0*) and an azimuthal index l, which gives the topological charge, i.e. the number of 2π phase windings.

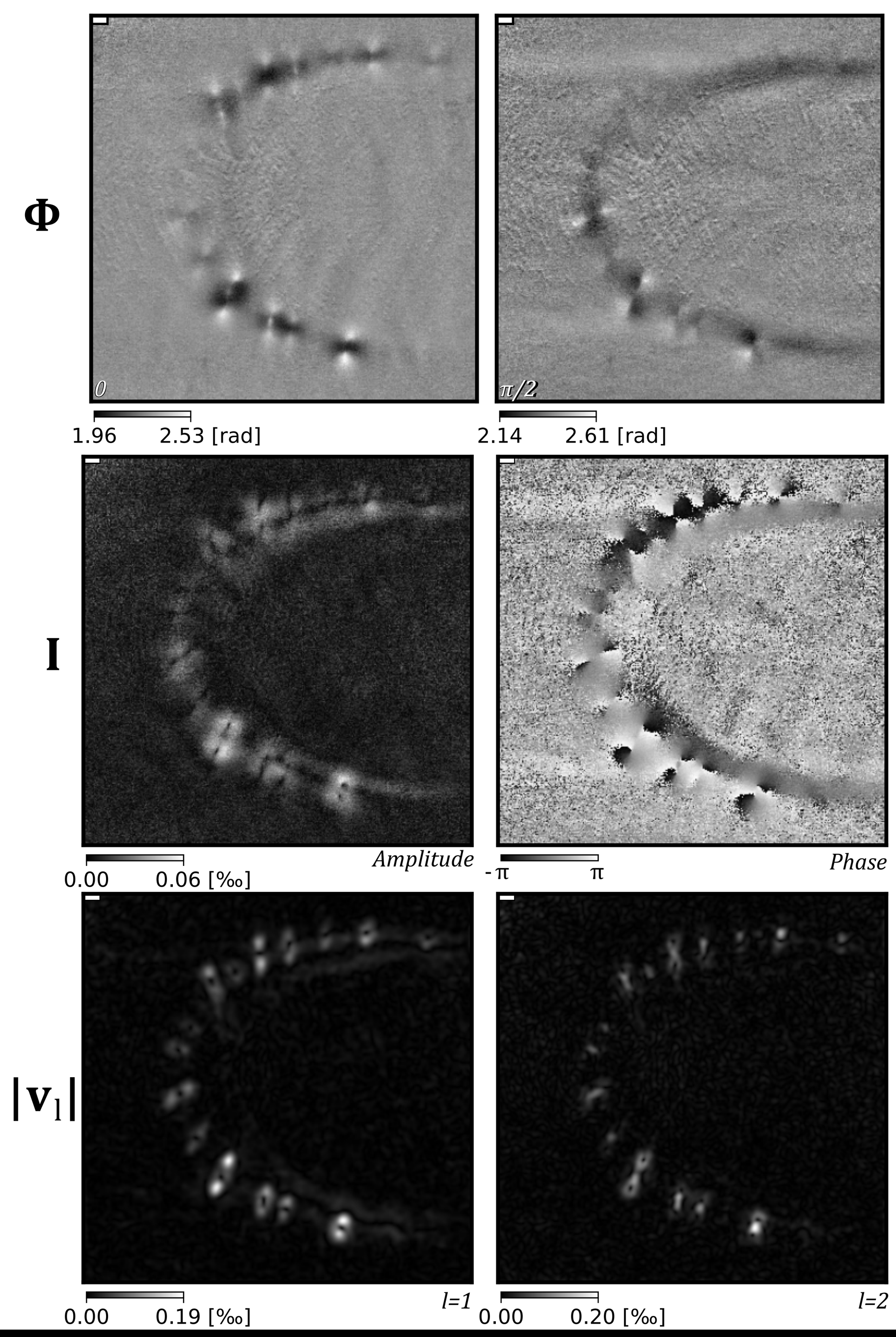


$$\mathbf{v}_l = \mathbf{I} \star \Lambda_l$$

IV. RESULTS

Results of an M-ECT experiment with phase shifting and vortex cross-correlation performed on an inconel sample with real cracks. kHz, Hz and a total acquisition time of 1 s. The thermal camera used was a FLIR X6541sc operating at 220 fps. As explained in the methods section induction current directions are changed, this is achieved using a proprietary inductor design.

Two of phase images ( ) for the measurment are shown on the first row. The result from the PS procedure can be seen in the second row, to the left the amplitude and to the right the phase, note that multiple cracks can be identified. In the third row we observe the results for the cross-correlation with (left) and (right), crack visibility is clearly enhanced. Scale bars are 1 mm.



V. CONCLUSIONS

This work demonstrates that the application of vortex cross-correlation to M-ECT phase images results in a systematic enhancement of image contrast. A consistent and reproducible methodology for applying this processing to phase images obtained from M-ECT inspections has been defined. Moreover, the improved contrast and clearer isolation of defect-related features produced by this approach provide a suitable basis for subsequent automated analysis, and open the possibility of integrating deep learning methods for automatic defect detection—an avenue that is currently being explored.

1. C. Ibarra-Castanedo, J. R. Tarpani, X. P. Maldague, European Journal of Physics. 34, S91 (2013). | 2. B. Oswald-Tranta, Quantitative InfraRed Thermography Journal. 19, 239–260 (2022). | 3. U. Netzelmann et al., Quantitative InfraRed Thermography Journal. 13, 170–181 (2016). | 4. B. Urtasun, I. Andonegui, E. Gorostegui-Colinas, Scientific Reports. 13, 17540 (2023). |5. F. Pampaloni, J. Enderlein, arXiv preprint physics/0410021 (2004).

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