# DIAGNOSTICS OF DEGRADATIVE CHANGES IN PARAMAGNETIC ALLOYS WITH THE USE OF LOW FREQUENCY IMPEDANCE SPECTROSCOPY

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## Abstract

In the article theoretical bases of the low frequency impedance spectroscopy method and possibilities of its use in the diagnostics of paramagnetic alloys used in aeronautics are explained. The main focus is put on description of interaction of electromagnetic radiation with the material, eddy currents excited in the material (carrier of diagnostic data), modelling of the material and a given diagnostic problem with an equivalent RLC circuit, method of exciting and observation of eddy currents and bases of qualitative and quantitative analysis of the test signal. The knowledge necessary to consciously use eddy currents in NDT and SHM tests directed on the identification of an early phase of material degradation (the phase preceding an open crack) is also of particular importance in the article. The applied measurement instrumentation and sample results of in-house and other research centres' tests are presented. The in-house tests were performed on objects made of the ASTM 289 class C austenitic steel and ALSi13Mg1CuNi aluminium alloy and on paramagnetic materials used in transport and power industry, whose values of magnetic susceptibility are similar, but their composition, microstructure and other mechanisms of the early phase of fatigue degradation are different. Taking them as an example, the need of taking into consideration the specificity of aeronautical materials and diagnostic problem being solved by the selection of the frequency of electromagnetic radiation, methodology applied in preparation of test methods and diagnostic criteria is highlighted.

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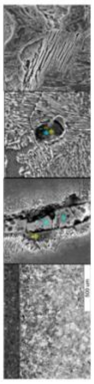
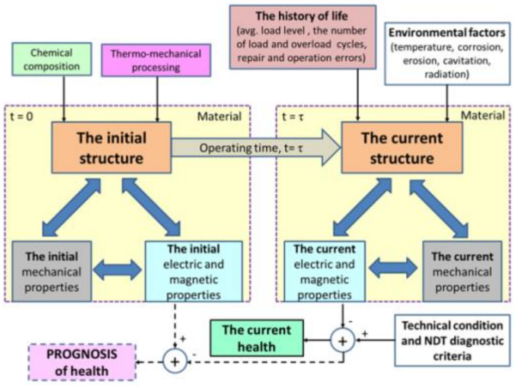
## Introduction

How to diagnose the degree of fatigue degradation of paramagnetic alloys?

## Low frequency impedance spectroscopy

There is a relationship between the state of microstructure (chemical composition, quality and level of fatigue degradation) and electrical and magnetic properties of the material.

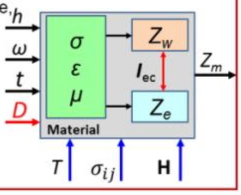




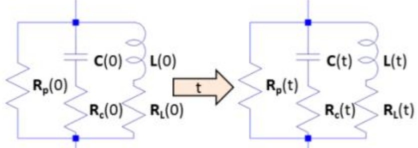

Expected change in **electrical impedance** $Z_e$ and **wave impedance** $Z_w$ of the material before fracture

$$Z_m = Z_1 + jZ_2 = f(Z_e, Z_w) = f(\sigma, \varepsilon, \mu, \omega, h, D, t)\Big|_{T,\sigma_{ij},\mathbf{H}}$$

where: $Z_m$ – Electromagnetic impedance of material,
$Z_1$, $Z_2$ – real and imaginary part of the impedance,
$\sigma$ – the electric conductivity,
$\varepsilon$ – the electrical permittivity,
$\mu$ – the magnetic permeability,
$\omega$ – the angular frequency,
$h$ – depth from the surface,
***D* – level of structure degradation**,
$t$ – lifetime
$I_{ec}$ – eddy currents




The paramagnetic metals have a conductivity $\sigma > 10^6$ S/m - substitute circuit is a **real inductor**. Electrical conductivity of the metal describes the Drude model.




$R \propto 1/\sigma$

$C \propto \varepsilon$

$L \propto \mu$

$$Y_e \equiv \frac{I}{U} = Y_R + Y_L + Y_C = \frac{1}{Z_e} = \frac{1}{R_p} + \frac{1}{R_L + j\omega L} + \frac{1}{R_C - j\frac{1}{\omega C}}$$

$$\sigma = \sigma_1 + j\sigma_2$$

$$\sigma_1 = \sigma_{DC} + \omega\varepsilon_2(\omega) = \sigma_{DC}/(1+\omega^2\tau^2) \qquad \sigma_2 = \omega\varepsilon_1(\omega) = \omega\tau\sigma_{DC}/(1+\omega^2\tau^2)$$

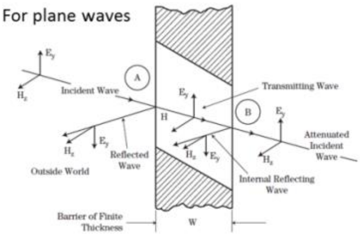
$$\varepsilon_1 = \varepsilon_c - \frac{\omega_p^2}{\omega^2 + 1/\tau^2} \qquad \varepsilon_2 = \frac{\omega_p^2}{\omega\tau(\omega^2+1/\tau^2)}$$

From DC to 10 MHz $\sigma_1 \cong \sigma_{DC}$ and $\sigma_2 \cong \omega\tau\sigma_{DC}$

$$Z_w \equiv \frac{E_0^-(x)}{H_0^-(x)} = \sqrt{\frac{j\omega\mu}{\sigma + j\omega\varepsilon}}$$

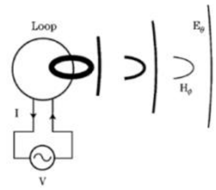
is described by:
- ✓ source type of wave
- ✓ reflection losses, $R_E$, $R_M$
- ✓ absorption loss, A

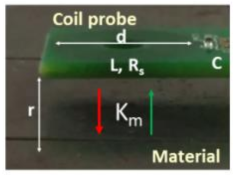
For plane waves




$$R_E = f(\sigma/\mu, r^2, \omega^3) \qquad R_M = f\left((\sigma/\mu)^{0.5}, r, \omega^{0.5}\right) \qquad A = f(\sigma\cdot\mu, \omega)$$

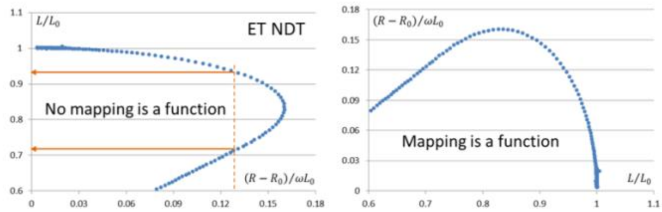
## Measurement (contactless method, near field)



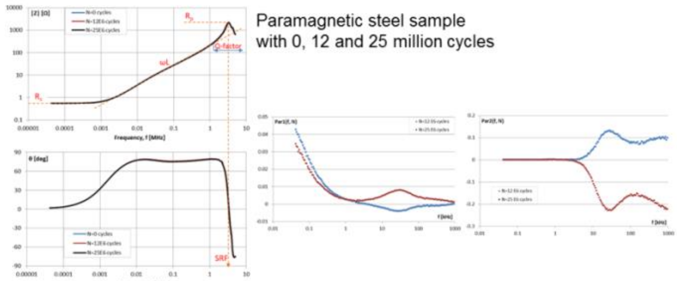




$$Z_S = f(Z_e, Z_m, K_m) = f\left(\underbrace{\omega, r}_{\text{measurement parameters}}, \underbrace{\sigma, \varepsilon, \mu, W}_{\text{material parameters}}, \underbrace{r/d, L, R_S, Q, SRF}_{\text{probe parameters}}\right)$$

### Impedance plane

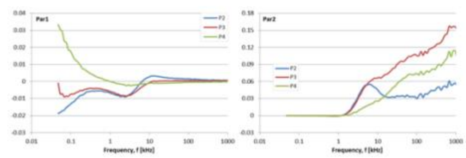



## Examples of results



Paramagnetic steel sample with 0, 12 and 25 million cycles

Aluminum alloys samples with different quality of structure



## Conclusion

The electric and magnetic parameters of the material ($\sigma$, $\varepsilon$, $\mu$) and the level of its structure degradation (damage) can be identified using low frequency impedance spectroscopy method.

Impedance NDT of metal can be implemented using low-cost measurement path.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DGZfP German Society for Non-Destructive Testing

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