**Probabilistic multi-modal UT and EM data fusion for hybrid in-motion rail damage, detection, localization, and characterization**

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ABSTRACT

This work presents a hybrid probe sensing system for rolling contact fatigue (RCF) damage in rails at high speeds. The multi-modal probe combines the nondestructive evaluation (NDE) methods of ultrasonic testing (UT) with surface Rayleigh waves generated and detected using electromagnetic acoustic transducers (EMAT) and electromagnetic testing (EM) using magnetic flux leakage (MFL) with the motion-induced eddy current (MIEC) effect. The combination of these NDE methods allows for data fusion which enables RCF damage detection, localization, and characterization.

The hybrid probe design integrates the UT and EM sensing modules. The UT sensing module takes advantage of 1 MHz Rayleigh surface waves for surface and near-surface inspection of rails. While the UT module exhibits excellent damage detection capabilities, the EMAT’s large sensing footprint hinders high-resolution defect localization. The EM module, on the other hand, has high-resolution defect localization potential but lacks reliable defect detection. Gross damage detection is carried out with the UT sensing module data. Using the gross damage regions, damage locations are more accurately determined using the EM dataset. From the measured damage locations, a spatial probability density function (PDF) is constructed, which quantifies the probability that any given spatial location will contain a defect.

Using the spatial PDF, ultrasonic transmission coefficients, *Tc*, are determined which align with previous numerical work carried out by the authors. For enhanced damage characterization at high speeds, the motion-induced eddy current (MIEC) effect shows great potential according to the work carried out by Piao et al.

This work explores the use of non-contact sensing modules (UT and EM) to enhance the inspection system’s defect size bandwidth. Additionally, a data fusion process is proposed which utilizes the UT module’s strong defect detection capabilities and the EM module’s localization capabilities to produce a reliable spatial PDF. For damage characterization, the UT Tc values and the MIEC features are explored. Moving forward, the authors intend to test the hybrid probe system at high-speed on rail samples, and further explore the damage characterization capabilities of the hybrid probe.

**Keywords:** hybrid probe, ultrasonic testing, motion-induced eddy current, RCF damage, in-motion inspection