ALETHEIA

A Multi-Frequency Eddy Current Pulsed Thermography Dataset for Neural Operator Learning in Nondestructive Testing

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4,782 defect instances · **6** defect types · **10** frequencies · 1–100 kHz · **13** temperature frames

Scan for code & data

NEURAL INFORMATION PROCESSING SYSTEMS

STAGE 1 / ALETHEIA DATASET & BENCHMARK

Surface temperature S → volumetric heat source Q

Recover internal heat sources from sparse and noisy surface temperature measurements.
ALETHEIA pairs simulated surface measurements with the corresponding 3D heat sources.
The benchmark tests how well models generalize across frequencies and crack geometries.

→

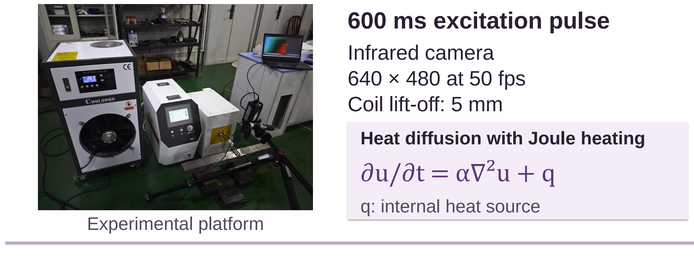
STAGE 2 / DOWNSTREAM INFERENCE FOR RAIL INSPECTION

Reconstructed Q → crack angle, length, depth

ECPT uses induction heating and infrared imaging for non-destructive testing (NDT).
The recovered heat field helps estimate the angle, length and depth of hidden rail cracks.
Recovering detailed 3D crack shapes remains challenging.

Why multiple frequencies?

Low frequencies give deeper eddy-current penetration.
High frequencies concentrate currents and heat near the surface.



The two defects look similar at 9 kHz and distinct at 25 kHz.

Why infer the heat source first?

High-Q regions align with defect surfaces, and Q-value decay indicates propagation direction. Low-Q regions indicate cavities.

Rail thermography experiment

Experimental platform

600 ms excitation pulse

Infrared camera
640 × 480 at 50 fps
Coil lift-off: 5 mm

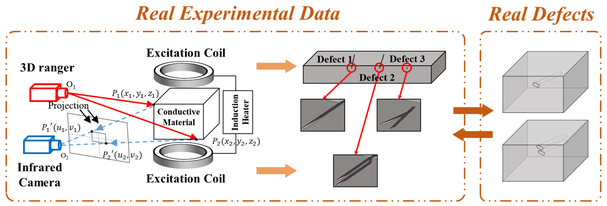
Heat diffusion with Joule heating

$$\partial u/\partial t = \alpha \nabla^2 u + q$$

q: internal heat source

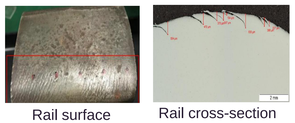
The ALETHEIA dataset

Real thermography calibrates the COMSOL simulations.



Experimental setup and subsurface defect geometries

Rolling contact fatigue cracks



Rail surface · Rail cross-section

Fatigue cracks can start at the surface and extend into the rail head.

Views show different rail specimens.

What ALETHEIA contributes

- **Electromagnetic–thermal coupling**
  Open dataset for eddy current thermography.
- **Multi-frequency excitation**
  1–100 kHz probes different depths.
- **Three-dimensional, time-resolved fields**
  3D heat sources and temperature sequences.
- **Simulation and experimental measurements**
  IR data calibrate the simulations.

ECPT in rail inspection

FATIGUE DAMAGE

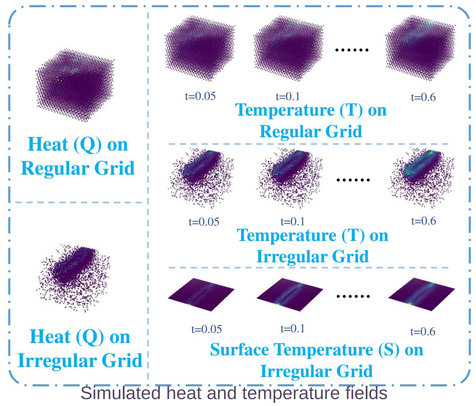
Repeated wheel loads can cause rail-head cracks.

NON-CONTACT TEST

A coil heats the rail.

An IR camera records surface Temperatures as the rail cools.

Fields and benchmark tasks



Simulated heat and temperature fields

Q2T
Source-to-temperature prediction

T2Q
Temperature-to-source reconstruction

T2T
Temporal forecasting
11 input → 2 future frames

S2Q
Surface-to-source reconstruction

Generalization under distribution shifts

Normal
All ten frequencies in both splits.

Frequency-band OOD
Hold out a low, mid or high band.

Single-frequency OOD
Train on one frequency.
Test on the other nine.

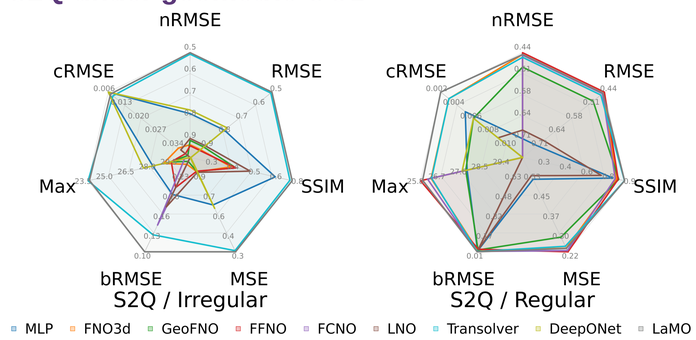
Geometric OOD
Train on five defect types.
Test on the unseen sixth.

Benchmark results

Model	Irregular grid								Regular grid							
	Normal		Band OOD		SFO		Geom-OOD		Normal		Band OOD		SFO		Geom-OOD	
	T2Q	S2Q	T2Q	S2Q	T2Q	S2Q	T2Q	S2Q	T2Q	S2Q	T2Q	S2Q	T2Q	S2Q	T2Q	S2Q
FNO	0.175	0.292	0.232	0.424	0.255	0.716	0.390	0.773	**0.029**	**0.092**	**0.038**	**0.119**	**0.119**	0.302	**0.066**	**0.221**
GeoFNO	0.217	0.309	0.257	0.352	0.287	0.396	0.249	0.566	0.061	0.093	0.075	0.147	0.164	**0.164**	0.089	0.222
Transolver	0.112	**0.160**	0.135	**0.245**	**0.175**	**0.347**	**0.175**	0.396	0.041	0.098	0.051	0.147	0.137	0.324	0.070	0.245
LaMO	**0.077**	0.169	**0.125**	0.247	0.177	0.363	**0.175**	**0.381**	0.039	0.098	0.050	0.163	0.126	0.315	0.069	0.240

Surface-only input increases reconstruction error
For Transolver on the irregular grid under geometric OOD, MSE rises from 0.175 (T2Q) to 0.396 (S2Q).

S2Q under geometric OOD



CODE & DATA
https://github.com/sherlock-0327/ALETHEIA/

PAPER
https://arxiv.org/abs/2611.11252

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