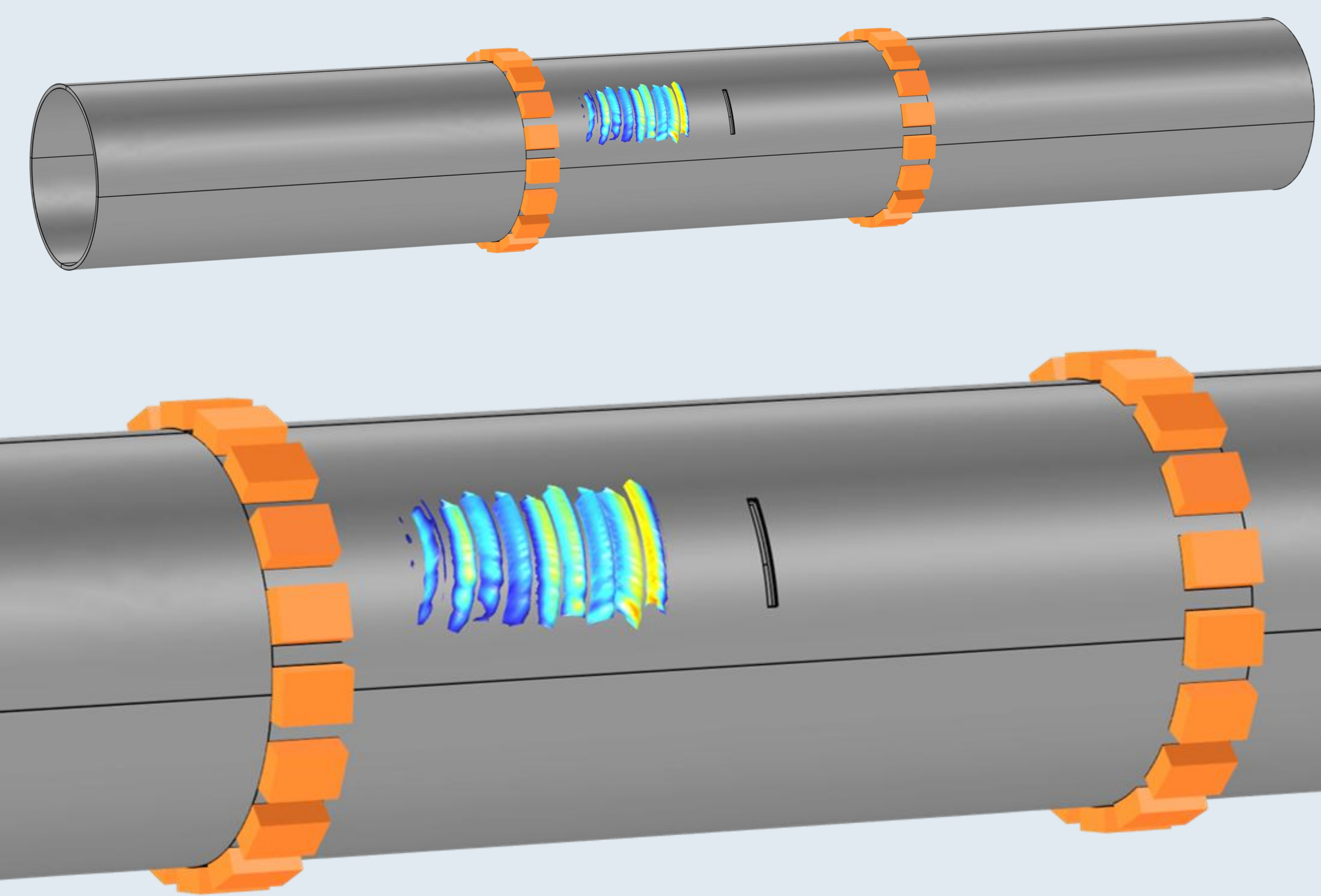




Physics-Based Digital Twin Framework for Guided Wave Inspection of Pipelines

The EMUS-TWIN project combines guided wave inspection with physics-based simulation for pipeline monitoring. A digital twin framework enables efficient and quantitative corrosion assessment.

Dr. Sascha Thieltges¹

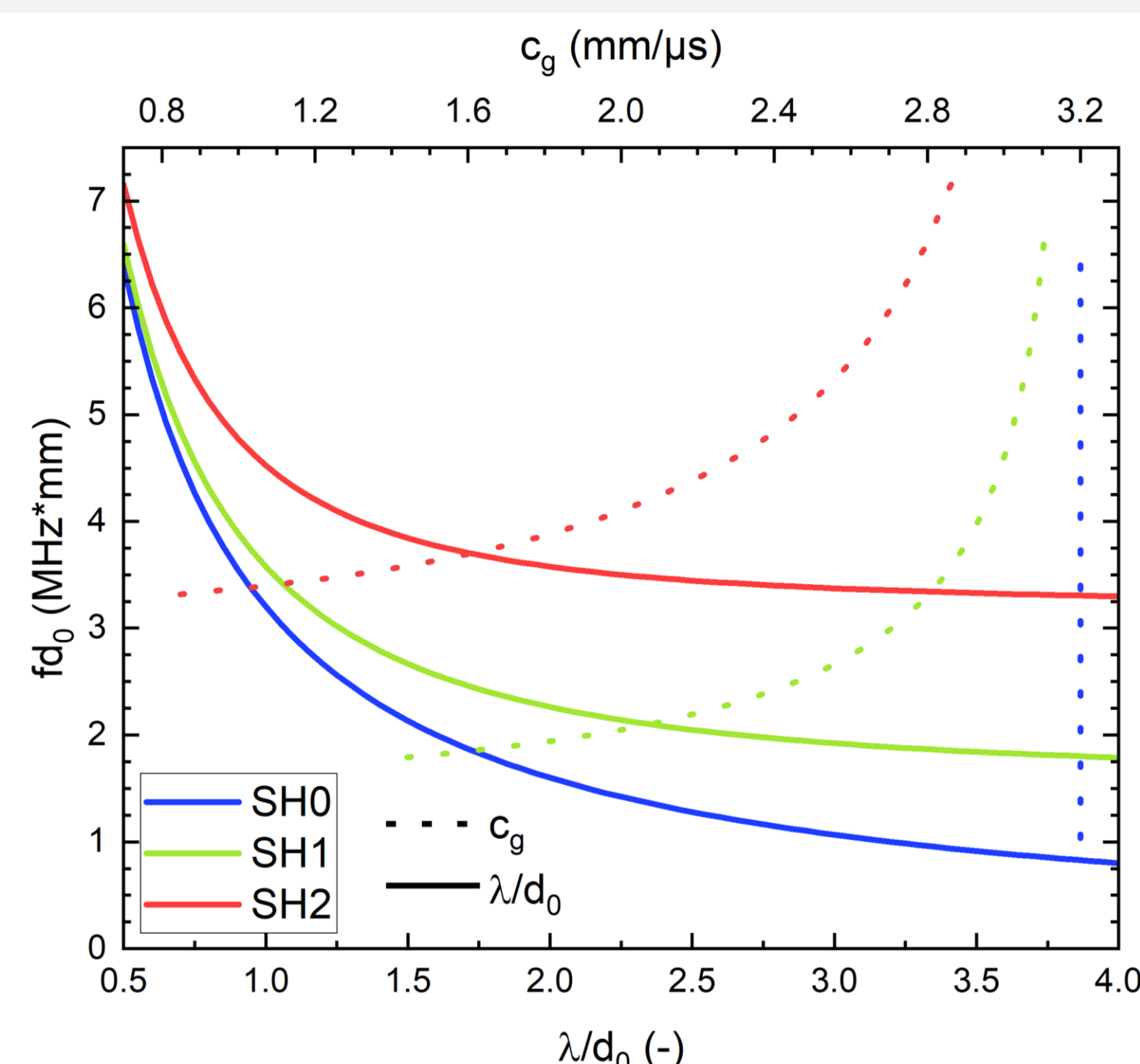
1. Fraunhofer Institute for Nondestructive Testing, Saarbrücken, Germany

Abstract

Guided ultrasonic waves (GW) enable the inspection of large pipeline sections, but quantitative corrosion characterization remains challenging due to complex wave–defect interactions.

Within EMUS-TWIN, a three-dimensional transient finite element model is implemented in COMSOL Multiphysics® to simulate shear horizontal (SH) guided waves and their interaction with localized corrosion defects. Parameterized defect configurations are used to investigate wave scattering and generate simulation datasets.

These datasets form the basis for surrogate models that approximate high-fidelity simulations at reduced computational cost. Combined with optimization algorithms and experimental data, they enable inverse corrosion characterization within a physics-based digital twin for efficient pipeline condition assessment.



Dispersion characteristics of the *SH0*, *SH1*, and *SH2* modes in terms of fd_0 , λ/d_0 , and group velocity c_g .

Methodology

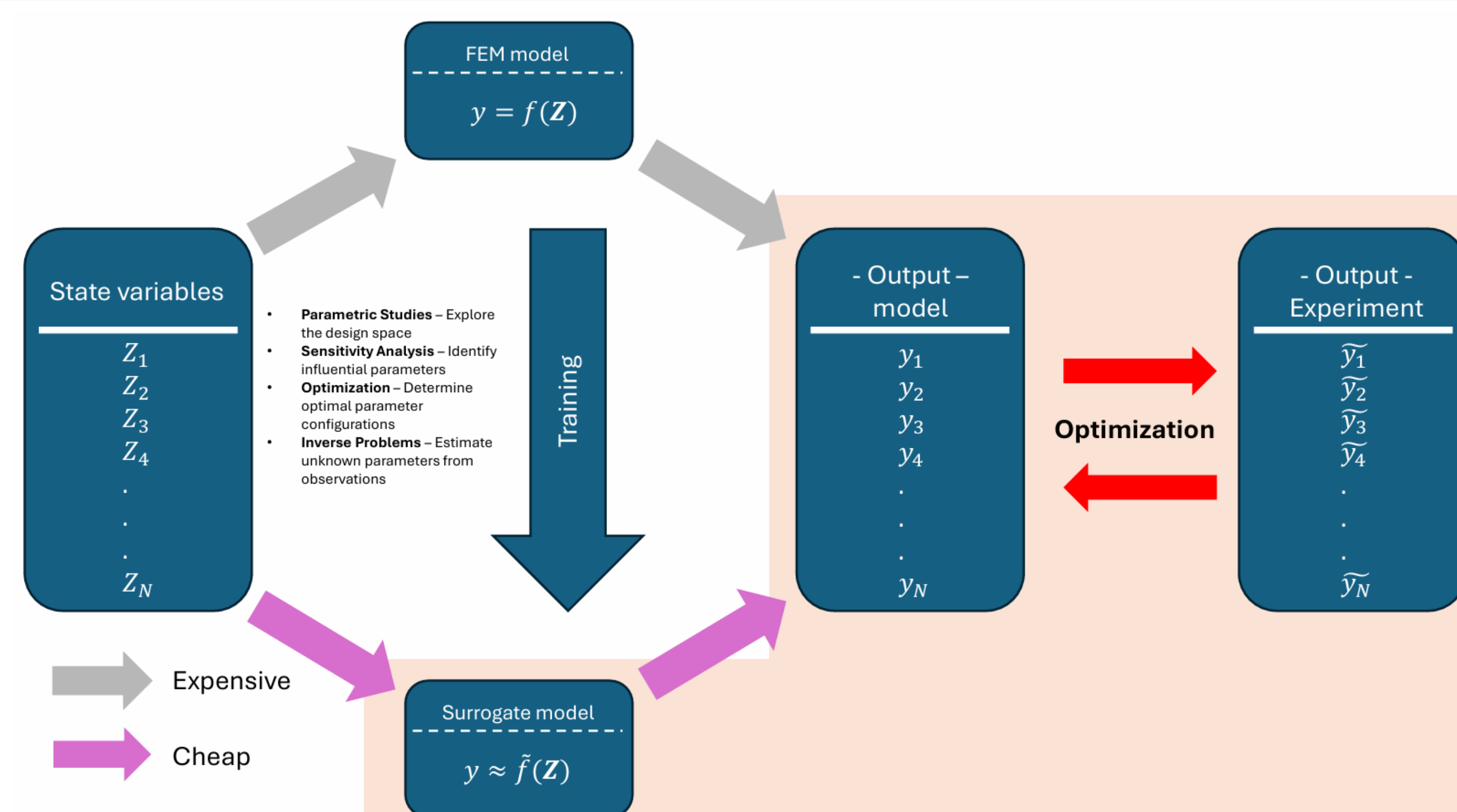
GW excitation is represented by line forces matching the experimental sensor (EMATs) configuration, enabling excitation of *SH0*, *SH1*, and *SH2* modes. Two circumferential rings with 12 transducers each provide angular information through different transmitter–receiver pairings.

The receiver signal is reconstructed from the simulated displacement field without explicitly modeling electromagnetic transduction. A dedicated algorithm convolves the displacement distribution across the receiver cross-section with the known magnetic field distribution. Rectangular defects are parameterized to generate signals for surrogate-model training. The surrogate predicts receiver signals for different defect configurations and is coupled with Differential Evolution for inverse defect characterization.

Results

The developed framework establishes a direct link between high-fidelity wave propagation simulations and computationally efficient defect characterization. The surrogate model transfers the physical information contained in the FEM-generated signals into a representation suitable for iterative optimization. This enables numerous defect configurations to be evaluated without repeatedly solving the computationally expensive full FEM model.

By integrating experimental signals through inverse optimization, the approach provides the basis for estimating unknown defect parameters from measured data. The framework therefore bridges detailed physics-based modeling and efficient data-driven evaluation, forming the foundation for a digital twin capable of quantitative pipeline condition assessment.



Physics-based digital twin workflow combining FEM, surrogate modeling, experimental data, and inverse optimization.

REFERENCES

- [1] P. Jäckel, F. Niese and C. Boller. “Quantitative detection of shallow corrosion damage by targeted use of the dispersive behavior of guided wave modes”. In: IWSHM/Stanford (2013). doi: 10.24406/publica-fhg-382439.
 [2] C. L. Willey et al. “Guided wave tomography of pipes with high-order helical modes”. In: NDT & E International 65 (2014), doi: 10.1016/j.ndteint.2014.03.010
 [3] R. Howard and F. Cegla. “Detectability of corrosion damage with circumferential guided waves in reflection and transmission”. In: NDT & E International 91 (2017), doi: 10.1016/j.ndteint.2017.07.004.