TECHNICAL SCIENCES

FRACTAL DIAGNOSTICS A NEW PARADIGM FOR THE OPERATIONAL MONITORING OF GAS PIPELINE SYSTEMS

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Abstract

The preservation of environmental integrity and the sustainability of global energy supplies depend heavily on maintaining the structural and operational soundness of gas transport pipelines. Standard non-destructive testing and routine technical diagnostics frequently fail to identify embryonic degradation, minute leakages, or volatile operational irregularities. This limitation stems from the fact that such anomalous signatures are typically obscured by the non-linear, non-stationary, and highly stochastic background noise characteristic of industrial data. To address these technical shortcomings, this study introduces an innovative diagnostic framework grounded in the principles of fractal geometry. By treating variations in fluid pressure, volumetric discharge, and acoustic emissions as fundamentally chaotic time-series, we implement the Hurst exponent (H) alongside Multifractal Detrended Fluctuation Analysis (MFDFA) to isolate latent structural configurations and track the dynamic fractal dimension (D) reflecting the behavior of the transport system. The reliability of this analytical model was verified through empirical testing on industrial datasets embedded with simulated physical defects. The computational outcomes reveal that fractal descriptors possess superior sensitivity regarding the identification of minor transitions in system dynamics. Conclusively, this methodology transitions industry standards from conventional, reactive repair protocols to high-fidelity, predictive operational tracking, providing a powerful mathematical instrument for contemporary intelligent pipeline networks.

Keywords: Gas transmission, Fractal geometry, Structural health monitoring, Anomaly isolation, Chaotic signal processing, Long-range dependence.

Introduction: Industrial gas pipeline distribution networks represent highly intricate, capital-intensive engineering infrastructures that continually experience environmental fluctuations, internal chemical degradation, and cyclic mechanical loads. Traditional diagnostic paradigms, including conventional transient pressure wave techniques and Fourier-transformed spectral evaluations, operate predominantly under idealized linear assumptions. In reality, the complex hydrodynamics governing compressed gas flows—particularly during operational shifts or localized structural failures—are fundamentally non-linear and exhibit chaotic behavior. As a direct consequence, early-stage structural anomalies remain hidden beneath dense layers of stochastic operational noise, frequently resulting in catastrophic detection lags or erroneous system alerts. To mitigate these analytical barriers, the present research utilizes fractal analysis as an advanced mathematical topology engineered to quantify the inherent self-similarity and non-Euclidean irregularities of pipeline sensor streams.

Methodology: The mathematical architecture of the formulated diagnostic protocol centers on evaluating the behavioral complexity of non-stationary time-series captured by localized pipeline sensor arrays. This computational framework is executed through a sequential three-tier process:

1. Signal Pre-processing: High-frequency pressure and acoustic waveforms undergo initial filtering to eliminate erroneous data spikes and measurement artifacts, while carefully preserving the underlying stochastic dynamics and natural self-affine fluctuations of the flow.
2. Quantification of Fractal Dimensions: The topological complexity and geometric roughness of the processed signal trajectories are indexed via the application of the box-counting algorithm to establish the baseline fractal dimension.
3. Multifractal Spectrum Characterization: Recognizing that intricate fluid dynamics within a pressurized pipeline cannot be comprehensively modeled by a single, global fractal scaling factor, Multifractal Detrended Fluctuation Analysis (MFDFA) is integrated into the workflow to capture multi-fractional characteristics across varying time scales.

Conclusion: The proposed diagnostic algorithm was rigorously evaluated utilizing empirical operational parameters that simulated both optimal baseline conditions and micro-structural anomalies, including localized wall thinning from corrosion and low-volume (**0.5%**) product leakages. The formulation of these fractal-oriented monitoring and control methodologies marks a transformative evolution in pipeline integrity management. By exploiting the mathematical attributes of deterministic chaos and structural self-similarity, this diagnostic framework achieves precise identification of operational deviations at their earliest embryonic stage. Seamlessly incorporating this fractal-driven framework into current supervisory control systems (such as SCADA) holds the potential to significantly diminish ecological hazards, mitigate the probability of sudden pipeline ruptures, and streamline predictive maintenance logistics for modern smart energy infrastructures.

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