ENT1099ME03 - AI Transformer-Based Multi-Sensor Blade Fault Diagnosis Using Vibration and Acoustic Emission Signals in Rotating Machinery

Principal Investigator

Dr. Ahmed Abdelrhman	ahmed.abdelrhman@polytechnic.bh
Polytechnic ID: 12010824	**Department/School**: Engineering

Programme	EN1099 PhD in Engineering
Research Area and Specialization:	Mechanical Engineering – Condition Monitoring, Predictive Maintenance, Artificial Intelligence, Deep Learning, Acoustic Emission, Rotating Machinery Diagnostics
Company Endorsement	Bapco
Industry mentor	Dr. Ismaeel Husain - VP - Health, Safety, Security, & Environment (HSSE) ismail.ahmed@bapcoenergies.com Dr. Hazem Hasan-Manager - Offsites & Utilities Engineering hazem.hasan@bapcoenergies.com

Background of the problem

Blade fault diagnosis in rotating machinery remains a major challenge due to the nonlinear and noisy nature of vibration and acoustic emission signals.

Conventional signal processing methods such as FFT and wavelet analysis are highly dependent on manual feature extraction and expert interpretation, making them unsuitable for fully automated intelligent monitoring systems.

Recent advances in deep learning have significantly improved machinery fault diagnosis capability. CNNs and LSTMs have demonstrated improved feature learning performance compared to shallow machine learning approaches. However, these methods still face limitations in capturing long-range temporal dependencies and maintaining robustness under noisy operating conditions.

Transformer architectures have recently emerged as powerful sequence-learning models due to their self-attention capability and parallel processing efficiency. Nevertheless, applications of Transformers for blade fault diagnosis remain very limited, particularly for multistage rotor systems.

In addition, most existing studies rely only on vibration monitoring. Acoustic emission signals provide complementary high-frequency fault information capable of detecting incipient blade damage earlier than vibration analysis alone. However, very limited studies have explored integrated vibration and AE fusion for intelligent blade fault diagnosis.

This research addresses these gaps by developing an explainable Transformer-based multi-modal diagnostic framework integrating vibration and acoustic emission signals for robust predictive maintenance applications.

List of publications related to the field

1. A Novel Hybrid Deep Learning Approach Using Convolutional Neural Network–Transformer With Cross-Attention Mechanism for an Effective Minor Blade Fault Detection, International Journal of Rotating Machinery, 2026, 7970678, 30 pages, 2026.

https://doi.org/10.1155/ijrm/7970678

https://onlinelibrary.wiley.com/doi/full/10.1155/ijrm/7970678

2. Hybrid Deep Learning Model for Robust Blade Fault Diagnosis in Multistage Rotor Systems, Journal of Engineering, 2025, 7764382, 41 pages, 2025.

https://doi.org/10.1155/je/7764382

https://onlinelibrary.wiley.com/doi/full/10.1155/je/7764382

3. Enhanced Blade Fault Diagnosis Using Hybrid Deep Learning: A Comparative Analysis of Traditional Machine Learning and 1D Convolutional Transformer Architecture. Engineering Reports, 7: e70202.

https://doi.org/10.1002/eng2.70202

https://onlinelibrary.wiley.com/doi/full/10.1002/eng2.70202

4. Early rotor blade fault detection in multi-stage rotor system based on wavelet analysis, 46th Annual Review of Progress in Quantitative Nondestructive Evaluation. (2019).

https://www.iastatedigitalpress.com/qnde/article/id/8721/

5. Condition Monitoring of Blade in Turbomachinery: A Review, Advances in Mechanical Engineering, 2014.

https://journals.sagepub.com/doi/full/10.1155/2014/210717

Research Objectives and Expected Outcomes:

Aim

To develop an understandable multi-modal Transformer-based framework for intelligent blade fault diagnosis and prognostics using vibration and acoustic emission signals in multistage rotor systems.

Objectives

To develop an explainable AI Transformer-based multi-sensor framework for blade fault diagnosis using vibration and acoustic emission signals.

To investigate and compare the diagnostic performance of vibration signals, acoustic emission signals, and fused multi-modal sensor data under different blade fault conditions.

To develop intelligent feature fusion and self-attention mechanisms for automatic extraction and classification of blade fault signatures under noisy industrial operating conditions.

To experimentally validate the proposed framework using a multistage rotor test rig and evaluate its robustness, accuracy, and predictive maintenance capability.

To investigate prognostic capability for early fault progression analysis and remaining useful life estimation in rotating machinery systems.

Research Design/Methodology

The research methodology consists of experimental investigation, signal acquisition, AI model development, and comparative validation phases.

Phase 1: Experimental Setup and Data Acquisition

A multistage rotor experimental rig will be utilized to simulate various blade fault conditions including:

- Blade tip rubbing
- Blade stage rubbing
- Blade cracking
- Blade twisting
- Blade loss
- Foreign object damage

Sensors used:

- Accelerometers for vibration monitoring
- Wideband acoustic emission sensors
- NI Data Acquisition System

Data will be collected under varying rotational speeds, loads, and noise conditions.

Phase 2: Signal Processing and Preprocessing

Raw vibration and AE signals will undergo:

- Signal segmentation
- Normalization
- Data balancing
- Noise augmentation
- Time-frequency analysis

Phase 3: Transformer-Based AI Model Development

The proposed framework will include:

- Temporal Transformer encoder
- Multi-head self-attention mechanism
- Cross-attention sensor fusion
- CNN-Transformer hybrid feature extraction
- Explainable AI module
- Prognostic prediction module

Three diagnostic frameworks will be evaluated:

- Vibration-only model
- Acoustic emission-only model
- Multi-modal fused model

Phase 4: Model Optimization and Validation

Optimization techniques:

- Hyperparameter tuning
- Cross-validation
- Ablation studies
- Noise robustness analysis

Performance metrics:

- Accuracy
- Precision
- Recall
- F1-score
- ROC-AUC
- Computational complexity

- Noise sensitivity

Comparative analysis will be conducted against:

- CNN
- LSTM
- ANN
- SVM
- Random Forest
- Ethical and Contextual Considerations

The study involves machinery experimentation only and does not involve human participants. Experimental safety procedures and industrial laboratory protocols will be followed throughout the research.

Significance and potential impact of research in Bahrain

The proposed research contributes significantly to intelligent condition monitoring and predictive maintenance technologies for rotating machinery. Blade failures in turbines and compressors can result in catastrophic equipment damage, production losses, safety hazards, and increased maintenance costs.

Therefore, early and reliable fault diagnosis is essential for industrial sustainability and operational safety.

The proposed multi-modal Transformer framework using vibration and acoustic emission signals is expected to improve diagnostic sensitivity, classification reliability, and fault localization capability. Integration of explainable AI will improve transparency and support maintenance decision-making processes.

The research will support:

Smart predictive maintenance systems

Reduced downtime and maintenance cost

Improved machinery reliability and safety

Industry 4.0 transformation

Intelligent industrial monitoring systems

Sustainable industrial operation

The project aligns strongly with Bahrain Vision 2030 and supports digital transformation and smart manufacturing initiatives in Bahrain.

Alignment with Bahrain's national research strategy

Contribution to Bahrain Society

The project supports Bahrain's transition toward smart manufacturing, industrial digitalization, and sustainable industrial operation by improving machinery reliability and predictive maintenance capability.

Alignment with Industry

The research directly supports:

- Oil and gas industries
- Power generation plants
- Manufacturing industries
- Aviation maintenance sectors
- Industrial predictive maintenance services

Benefits include:

- Reduced maintenance cost
- Improved operational reliability
- Enhanced industrial safety
- Reduced downtime
- Increased machinery lifespan
- Alignment with National Priorities

The project aligns with:

- Bahrain Vision 2030
- Industry 4.0 strategies
- Artificial intelligence and digital transformation initiatives
- Sustainable industrial development
- Smart maintenance technologies.