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RESEARCH PAPER

An Analytical Survey of Root Cause Analysis Techniques for Mechanical Failures

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***Abstract*—The failure of mechanical systems has a serious effect on safety reliability and continuity in the operations of important engineering systems such as energy, transportation, aerospace, and manufacturing. Complex interactions of material degradation, cyclic stresses, environmental exposures, design constraints, manufacturing variability, and operational practices contribute to these failures. Root Cause Analysis (RCA) has come out as a systematic and structured approach to the identification of the root technical, operational, and organizational causes of such failures. This paper survey of the RCA technique with mechanical failure investigation, in which the classification of failure mechanisms, hierarchical causation modeling, and systems engineering concepts are incorporated in the unified framework. The qualitative and quantitative instruments of analysis, such as Cause-Effect Diagram, Fault Tree Analysis (FTA), Failure Mode and Effects Analysis (FMEA), and reliability measures, such as MTBF, MTTR, failure rate, etc., are taken critically. Complex diagnostic methods, such as fractographic characterization, vibration signal processing, non-destructive testing (NDT), and finite element analysis (FEA), are integrated to promote evidence-based validation of failure mechanisms. The suggested analytical framework enhances methodological rigor, aids in the quantification of reliability, as well as allows proactive corrective actions in terms of sustainable mechanical systems functioning and reducing the risk.**

Keywords*—*Root Cause Analysis (RCA), Mechanical Failure Mechanisms, Fault Tree Analysis (FTA), Reliability Engineering, Non-Destructive Testing (NDT).

I. INTRODUCTION

Failure of mechanical systems is one of the most significant issues in contemporary engineering practice, which is especially relevant to the areas of power production, transport, aerospace, and production, where safety and continuity of operation are the primary factors [1][2][3]. The mechanical parts are subjected to complicated service conditions in terms of cyclic loading, thermal gradient, corrosive, dynamic loading and human intervention [4]. These causes of degradation mechanisms increase fatigue, wear, creep and fracture over time, and failure occurs. Other than the physical destruction of parts, mechanical systems breakdown can lead to unexpected downtime and cost, environmental degradation, and risks. Therefore, to improve the resilience of the system, it is important to establish the root causes of these failures in order to guarantee sustainable performance of the operations.

Root Cause Analysis (RCA) is the methodical process of determining causative elements employing strategies intended to offer a focus for issue identification and resolution. RCA has become an organized and systematic program to detect the underlying factors of failure incidences [5]. Instead of trying to identify only the immediate or visible causes, RCA looks into the series of events and contributory conditions leading to system breakdown. This approach focuses on the detection of the technical, operational, material and organizational shortcomings that could be hidden in the system. Identifying these underlying causes, RCA enables of long-term corrective and preventive measures which reduce recidivism and enhance the reliability of the system.

The reliability of Root Cause Analysis is determined by the strict selection and logical application of the necessary techniques of investigation of failures hese techniques represent a wide range of qualitative and quantitative tools, such as structured causal questioning, cause-effect modelling, fault-tree analysis, failure mode assessment, and statistical evaluation techniques. Such techniques are often supplemented by experimental diagnostics, material characterization, and condition monitoring data in mechanical engineering contexts [6]. A combination of such investigative methods allows performing a systematic investigation of causal-effect relationships between the observable failure modes and systemic of failure investigation should eventually in the context of reliability and risk assessment. The principles of reliability engineering give the quantitative values of probability of failure, prediction of component life, and performance of systems under uncertainty [7][8]. At the same time, risk assessment procedures can be used to assess the magnitude and impact of possible failures in support of priority actions on corrective measures [9][10]. On combining the results of RCA with reliability modelling and risk-based decision-making, organizations would be able to shift their focus towards responding to failures as they happen instead of employing reliability enhancement as a preventive measure. This paper is organized as follows: Section II Mechanical Failure mechanism and causation framework. Section III Theoretical and analytical framework of root cause analysis for mechanical failure Section IV. Advanced diagnostic technique for mechanical failure investigation in Section V Literature review, Section VI Conclusions and future work.

II. MECHANICAL FAILURE MECHANISMS AND CAUSATION FRAMEWORK

Mechanical failures arise from complex interactions between material behavior, applied stresses, environmental conditions, and operational practices. Understanding the underlying failure mechanisms and their associated causation pathways is fundamental to effective Root Cause Analysis (RCA). This section presents the primary mechanical degradation mechanisms and establishes a structured causation framework for systematic failure investigation

A. Classification of Mechanical Failure Mechanisms

Mechanical failure mechanisms refer to the physical processes that cause breakages and degradation of components. Stress conditions, material properties and exposure to the environment normally control these mechanisms is shown in Figure 1.

Fig. 1. Classification of Mechanical Failure Mechanism

Mechanical failure mechanisms are generally categorized based on the dominant mode of material degradation:

1) Fatigue Failure

Fatigue is a failure that is caused by cyclic or changing stresses which are the ultimate strength of the material but repeated with time. The cracking process starts around the points of concentration of stress, and then gradually grows [11]. Weaknesses Fatigue occurs in rotating shafts, gears, and structural elements to which the repetitive load is applied.

2) Ductile Fracture

Ductile fracture is one in which there is extensive plastic deformation before fracture. It is a normally high tensile stress fracture and is typified by necking and dimpled fracture surfaces. The mechanism is used to signify material yielding before rupture.

3) Brittle Fracture

Brittle fracture is one that does not have much or any plastic deformation, and once the fracture has started, it propagates very fast. It is commonly linked with low temperature, a high strain rate or material flaws.

4) Creep Failure

At high temperatures and under continuous tension, a sort of deformation known as creep takes place over time [12]. Creep causes a microstructural variation and ultimate failure, particularly in those elements as turbine blades as well as pressure vessels.

5) Wear and Corrosion

Wear takes place through mechanical contact between surfaces in contact that causes a loss of the material through friction. Environmental reactions degrade corrosion which is chemically driven. The two processes cause loss of cross-sectional area and structural integrity.

B. Root Cause Analysis Tools and Techniques

A systematic link between field observations and failure symptoms is used to conduct root-cause analysis. Numerous Root Cause Analysis Tools have emerged as broad principles for identifying root causes, as seen in Figure 2 [13]. These consist of the Why Analysis, the Current Reality Tree (CRT), the Cause-and-Effect Diagram (CED), the Interrelationship Diagram (ID), and the Multifare Analysis..

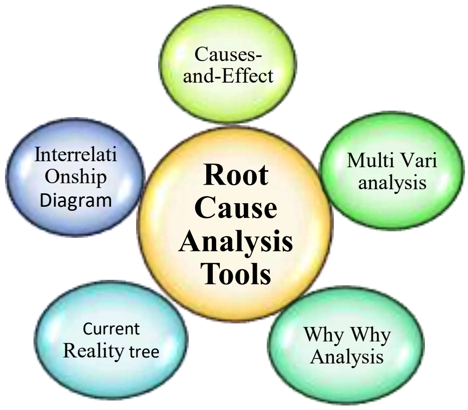

Fig. 2. Tools of Root cause analysis

1) Causes-and-Effect Diagram (CED

The causes in a cause and effect diagram are often divided into four major categories. In manufacturing cases, it is Manpower, Techniques, Materials, and Equipment [14]. For the administrative and service sectors, it consists of people, policies, practices, and tools.

2) Interrelationship Diagram (ID)

a technique to categorise possible causes or drivers by quantifying the correlations between elements. In each stage of the procedure, the relationships between the operations are displayed as "in and out." On the basis of logical sequence, the weight elements of in and out, which may comprise causes, consequences, or both, are established.

3) Current Reality Tree (CRT)

The Current Reality Tree is a technique that establishes logical, interconnected chains of linkages between undesirable sequences in order to determine their root causes. In terms of causality, factor relationships, usability, and engagement in the current situation, it depicts the reality.

4) Why why Analysis

A comprehensive knowledge of "what happened" is what root cause analysis is. In order to discover unresolved issues and information gaps, the team first reviews a "initial understanding" of the event. In addition to observing regular work procedures, the information-gathering process involves interviewing employees and workers who had a direct or indirect connection to the physical environment where the event and other relevant activities occurred.

5) Multi Vari Analysis

Positional, temporal, and cyclic errors may all be linked to root causes using this method. The aim is to ascertain whether a cause is recurrent in nature. It has re-occurred at specific intervals or not if it is repeated. Whether or if the causes have reappeared in a particular position. The following are the fundamental data needed for Multi Vari analysis:

- Number of day's sample data is taken.
- Number of shifts per day.
- Number of hours in a shift that sample data is taken.
- Number of units in an hour that sample data is taken from.
- Factors, which may include causes, effects, or both and their levels.

III. Theoretical and Analytical Frameworks of Root Cause Analysis for Mechanical Failures

A. Root Cause Analysis and Logical Modeling Techniques

The RCA has proven beneficial in a number of real-world applications:

- Preventing frequent failures that have a significant impact on maintenance and operation costs.
- Reactively resolving organizationally relevant complex issues.
- Analyzing recurring equipment or crucial process failures.
- Analyzing human error in method design and implementation.

There are five stages in RCA (Figure 3). As demonstrated, the problem's solution is derived simply from the problem's statement without a comprehensive examination of its root causes [15]. The root cause of an issue may be found using a variety of tools and methodologies for root cause analysis (RCA). Below is a quick description of a few of them:

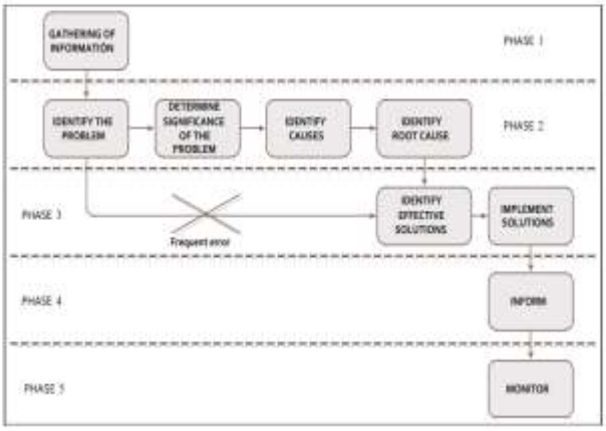

Fig. 3. Five Phase Root Cause Frameworks

A structured five-phase Root Cause Analysis (RCA) framework designed to ensure systematic problem resolution. The process begins with comprehensive information gathering, followed by clear problem identification and assessment of its significance. It then progresses through cause analysis and root cause determination, emphasizing the importance of avoiding premature solutions that may lead to recurring errors [16]. Effective remedial measures are found and put into place when the root problem has been determined. The final phases focus on communicating outcomes and continuously monitoring system performance to ensure sustained improvement and prevention of failure recurrence. This sequential structure promotes analytical rigor, traceability, and long-term reliability enhancement.

1) Logic tree (PROACT)

This approach arranges the chain of causes and effects' logical structure, starting with the failure or issue and ending with the fundamental factors that led to it (deductive analysis). In Figure 4, the logic tree topology is displayed.

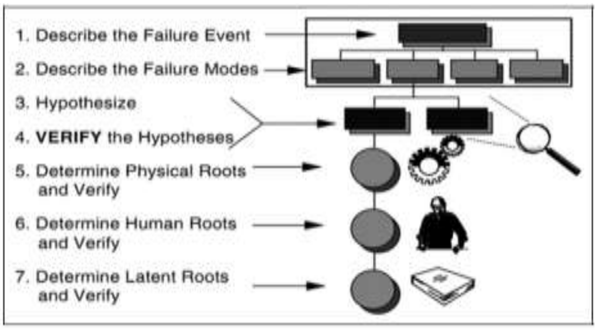

Fig. 4. Logic Tree Structure

Finally, each failure mode's root cause is revealed via the logic tree. There are usually three different kinds of causes:

- **Physical:** The component's mechanism of failure. It is the cause that immediately leads to failure. It is frequently the case that at this level, the failure's root cause is merely identified as a starting point.
- **Human:** Human error that influences failure occurrences either directly or indirectly.
- **Latent:** Demonstration of the organizational systems that describe the occurrence of root process human causes. The failure is not repeated, and only its eradication guarantees this.

2) FTA

The logical links between failure events are represented graphically by a fault tree, which branches the primary top event into events that contribute to it by analyzing causes and consequences. As a deductive process, FTA subtracts the other events from the top event. FTA can offer both quantitative and qualitative system information.

B. Causation Modeling and Hierarchical Cause Structure

Causation modelling refers to a structured method of analysis employed in the Root Cause Analysis (RCA) to map cause effect relationships that result in mechanical failure in a systematic manner [17]. It establishes the interaction of technical, operational, material and environmental factors to cause the failure and meets it with the help of the fault tree analysis and cause-effect diagrams.

1) Causation Modeling

Causation modelling is based on the creation of a rationale and explanation of how and why a failure took place. It determines interactions between mechanical, material, operational, and environmental variables, which culminated into system breakdown [18]. The models that are commonly used to model these relationships are analytical tools, including cause-and-effect diagrams, fault tree analysis (FTA), and event sequence reconstruction. Causation modelling can involve in mechanical systems, and it can include:

- Analysis of load stress interaction
- Material property evaluation
- Environmental influence assessment
- Maintenance and operational practice

2) Hierarchical Cause Structure

Hierarchical Cause Structure: In a hierarchical structure of causes, the causes are divided into several levels to prevent unjustified conclusions [19]. Mechanical failures are normally generally layered causation, which is divided into:

- **Immediate Causes:** Direct physical triggers (e.g., shaft fracture due to overload).
- **Contributing Causes:** Conditions that facilitated failure (e.g., misalignment, lubrication deficiency, corrosion).
- **Root Causes:** Fundamental systemic or design-related deficiencies (e.g., improper material selection, inadequate maintenance strategy, incorrect design assumptions).

C. Systems Engineering Approach to Failure Investigation

The systems engineering approach views mechanical failure as the result of interactions among multiple interconnected subsystems rather than an isolated component defect as shown in Table I. It integrates design, material behavior, manufacturing processes, operational conditions, maintenance practices, and human factors into a unified analytical framework.

TABLE I. SYSTEM-LEVEL INTERACTION MODEL FOR MECHANICAL FAILURE INVESTIGATION

System Element	Investigation Focus	Analytical Consideration	Impact on Failure Analysis
Design System	Load assumptions, safety factors	Design validation, stress analysis	Identifies design-related deficiencies
Material System	Material selection, heat treatment	Microstructural evaluation, property verification	Detects material incompatibility
Manufacturing System	Process variability, defects	Quality control records, defect analysis	Reveals fabrication-induced weaknesses
Operational System	Loading conditions, environment	Service data analysis, environmental assessment	Determines operational overstress
Maintenance System	Inspection frequency, lubrication	Maintenance history review	Identifies preventive gaps
Human & Organizational Factors	Procedures, training	Process compliance evaluation	Detects systemic management issues

D. Analytical Framework for Root Cause Analysis in Mechanical Failures

The framework is used to structure the investigation into logically progressive phases and incorporation of failure characterization, mechanism determination, causal modelling, diagnostic verification, and reliability-based evaluation is depicted in Table II. Such a structured representation provides methodological consistency, traceability of analytical reasoning, and evidence-based validation, which enhances the technical rigor and preventive efficacy of mechanical failure investigations.

TABLE II. STRUCTURED ANALYTICAL FRAMEWORK FOR ROOT CAUSE IDENTIFICATION IN MECHANICAL SYSTEMS

Investigation Stage	Analytical Domain	Engineering Objective	Methodological Approach	Technical Deliverable
Stage I	Failure Characterization	Define failure mode and operational boundary conditions	Visual examination, operational data acquisition, service history analysis	Formal failure definition
Stage II	Mechanism Determination	Identify physical degradation mechanism	Fractography, microstructural evaluation, material property assessment	Mechanism validation
Stage III	Causal Modeling	Establish hierarchical cause–effect relationships	Fault Tree Analysis (FTA), cause–effect mapping, event reconstruction	Root cause formulation
Stage IV	Diagnostic Verification	Validate hypothesized causes with empirical evidence	NDT techniques, vibration diagnostics, signal processing analysis	Evidence-based confirmation
Stage V	Reliability Quantification	Assess recurrence probability and performance degradation	Weibull modeling, stress–strength analysis, failure rate estimation	Reliability metrics
Stage VI	Risk Mitigation Strategy	Prioritize corrective and preventive actions	Risk matrix evaluation, criticality assessment, mitigation planning	Sustainable corrective framework

IV. ADVANCED DIAGNOSTIC TECHNIQUES FOR MECHANICAL FAILURE INVESTIGATION

The use of advanced diagnostic methods offers the technical basis of proper recognition of failure mechanisms and confirmation of root causes in the mechanical systems [20]. In comparison to the first-line inspection schemes, advanced diagnostics incorporates the characteristics of materials, non-destructive testing, signal analysis, and computer modelling to build quantitative and evidence-based conclusions. Such methods increase the accuracy, consistency and dependability of mechanical failure investigations.

A. Fractographic and Microstructural Characterization

Fractographic and microstructural characterization are the modern material research methods that are applied to identify the physical mechanisms of mechanical failure [21]. These procedures aim at studying the fracture faces and internal material architecture in order to determine the location of crack origin, crack propagation, and internal metallurgical defects. They give direct physical evidence that assists in the determination of root cause in the analysis of failures.

1) Fractographic Analysis

Fractographic Analysis Fractography is the study of the appearance of fractured surfaces in order to comprehend the mechanisms and reasons of failure of a component [22]. The fracture surface morphology can provide useful data about the failure mode, including fatigue, brittle fracture, ductile overload, creep rupture, or corrosion-assisted cracking. Common techniques include:

- **Optical Microscopy (OM):** It is applied during the initial observation of the surface and to monitor the pattern of crack.
- **Scanning Electron Microscopy (SEM):** Offers high-resolution visualization to identify fatigue striations,

cleavage facets, dimples, or intergranular fracture characteristics features.

- **Energy-Dispersive X-ray Spectroscopy (EDS):** This technique determines the elemental composition at the fracture site to identify inclusions, contamination, or corrosion products.

2) Microstructural Characterization

Microstructural analysis examine the internal structure of the material, such as grain size, phase distribution, inclusions, and heat-treatment effects [23]. It is required to assess the compliance of material properties with design requirements. Typical methods include:

- Metallographic sample preparation (sectioning, polishing, etching)
- Optical microscopy for grain structure evaluation
- Hardness testing and microhardness mapping

The microstructural examination might be used to identify the problem of heat treatment, irregular grain development, material segregation, porosity, or manufacturing

B. Vibration and Signal-Based Diagnostic Analysis

The state of mechanical equipment is reflected in vibration data. Analyzing them aids in the detection of anomalous operating situations and early defects that may eventually worsen and impair a machine's functionality [24]. Signal processing techniques are used to extract meaningful diagnostic output given complex vibration signal in a mechanical system are shown in Figure 5. These methods convert the raw time-domain signals into intelligible signals of fault conditions like imbalance, misalignment, bearing defect, gear damages, and resonance brief explanation of some of the important sophisticated processing methods are given below:

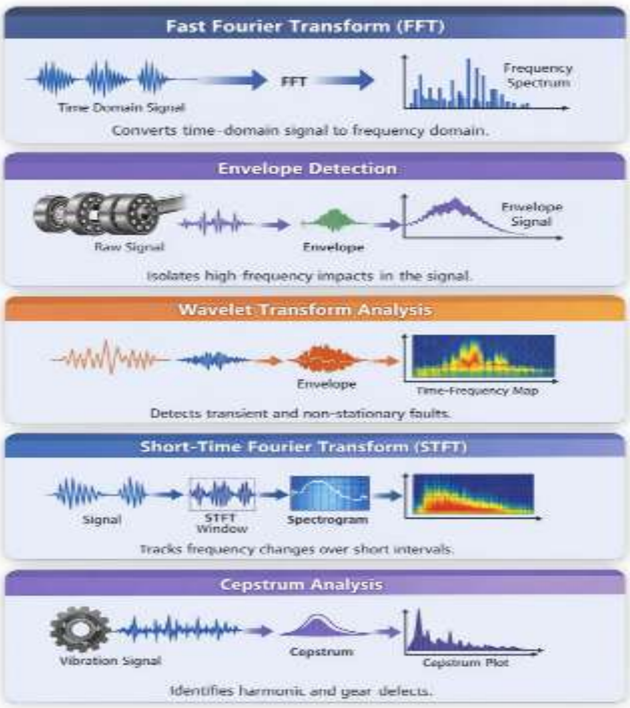

Fig. 5. Advanced Vibration Signal Processing Methods for Mechanical Fault Detection and Diagnosis

- **Fast Fourier Transform (FFT):** Time-domain vibration data are converted into the frequency domain using FFT, allowing to detect the primary fault frequencies related to rotating parts. It is especially useful in the identification of imbalance, misalignment, and defects of gears mesh.
- **Envelope Detection (Hilbert Transform):** Envelope analysis isolates high-frequency modulating signals produced by localized faults like bearing faults. It improves the weak repetitive impacts signatures that are usually obscured by background noise.
- **Wavelet Transform Analysis:** Wavelet transform offers time-frequency localization, which enables identification of non-stationary and transient fault signals. It is very appropriate in the determination of crack initiation and development of damage in changing operating conditions.
- **Short-Time Fourier Transform (STFT):** STFT is used to analyze the frequency changes within short time windows, thus it is useful to track moving changes in rotating machinery. It works well when the systems are working under the conditions of variable speed.

Cepstrum Analysis: Cepstrum analysis detects periodic structures in the frequency spectrum and is therefore useful in identifying gear tooth defects and anomalies in harmonics.

C. Computational Modeling and Finite Element Analysis (FEA)

Computational modeling plays a critical role in validating suspected failure mechanisms. FEA has become one of the most popular numerical techniques [25]because it can be used to a wide variety of continuum mechanics and many other fields. FEA is used in many different applications, including as:

- **Stress analysis:** An efficient computing method for elasto/viscoelastic solid material numerical simulation; A new technique for assessing the bus body's bending stiffness; research using the finite element method (FEM) to examine how starting stress affects the machining process.
- **Vibration and dynamic analysis:** Stiffeners for a typical panel are dynamically designed using finite element analysis and topology optimization; electric bus vibration is reduced during gear shifting and acceleration [26]. A method for creating finite element models in a semiautomated manner: application to mechanical equipment.
- **Biomechanics analysis:** Geometric properties of Multiple sidewall-type aneurysms and how they affect hemodynamic parameters.
- **Computational fluid dynamics:** Optimization of the drying environment for vortex flows and vortex suppression methods in the intake route of the pumping system for short-form spray dryers.
- **Cyclic loading:** The BOP gantry crane's fatigue and FSI analyses; Utilizing computational and experimental techniques to create optimal semitrailer axle supports.
- **Contact problems and wear:** The impact on the planetary rolling process of roll with passive section, Examining the fluid-solid thermal interaction in rolling bearings with oil-air lubrication.

- **Heat transfer analysis:** Optimizing an electric car battery pack's capacity to dissipate heat.
- **Reliability analysis:** The application of a novel sampling technique for dependability analysis based on the response surface method.

D. Non-Destructive Testing (NDT) and Condition Monitoring

Non-Destructive Testing (NDT) methods are commonly used in the investigation of mechanical failure in order to identify defects on either surface or subsurface without compromising the functionality of the component in Table III. Such methods come in handy especially in safety-critical structures like pressure vessels, rotating shafts, pipelines and welded joints [27]. NTD methods allow identification of evidence-based root causes and preventive maintenance strategies by providing early indications of discontinuities (including cracks, voids, inclusions, etc.,) and corrosion damage. Moreover, condition monitoring systems are integrated with them.

TABLE III. CLASSIFICATION OF COMMON NDT TECHNIQUES IN MECHANICAL FAILURE INVESTIGATION

NDT Technique	Working Principle	Detectable Defects	Typical Applications	Advantages	Limitations
Ultrasonic Testing (UT)	Internal discontinuities reflect high-frequency sound waves	Internal cracks, voids, inclusions	Pressure vessels, shafts, welded joints	High penetration depth, accurate sizing	Requires skilled operator
Radiographic Testing (RT)	X-rays or gamma rays penetrate materials and reveal variations in density	Internal porosity, weld defects	Pipelines, cast components	Permanent record, good for volumetric defects	Radiation safety concerns
Magnetic Particle Inspection (MPI)	Magnetic field induces leakage at surface defects	Surface and near-surface cracks	Ferromagnetic components, gears	Quick and cost-effective	Limited to ferromagnetic materials
Eddy Current Testing (ECT)	Electromagnetic induction may identify surface imperfections	Surface cracks, corrosion	Heat exchanger tubes, aircraft components	Fast and sensitive to small cracks	Limited penetration depth
Acoustic Emission (AE)	Detects stress-induced wave emissions from crack growth	Active crack propagation	Pressure systems, structural monitoring	Real-time monitoring	Complex signal interpretation

V. LITERATURE REVIEW

The research studies in mechanical failure investigation emphasize the application of Root Cause Analysis (RCA) techniques and reliability assessment methods across various engineering systems. Table IV presents a comparative analysis of these works, highlighting methodologies, key findings, challenges, and limitations.

G. P. M. Pinto (2026) identifying the failure's primary causes and assessing the system's technical dependability through field observations, pressure measurement, functional testing, fault tracing, supported by RCA and reliability metrics (MTBF, MTTR, and failure rate) degraded flange seals are the primary cause of air receiver leakage, contamination of the solenoid valve resulting in a loss of pilot pressure, and Insufficient cylinder impulse pressure due to starting-air valve seat wear. A failure rate of 0.00893 h^{-1}, an MTBF of 112 hours, and an MTTR of 2.5 hours were obtained from reliability calculations, demonstrating low operational reliability despite 97.8% availability. Leakage, contamination, and single-point failures are the main causes of system failure [28].

Chai et al. (2025) study reliability failure modes is delamination at either thermal or mechanical stress during packaging or reliability testing (e.g. Temperature cycling) show methods to determine failure mechanisms, root causes and corrective actions for delamination found at leaded packages. Failure analysis (FA) using CSAM (C-mode Scanning Acoustic Microscope), cross-sectioning and SEM (Scanning Electronic Microscope) has been conducted to determine the failure mechanisms of severe delamination found at die flag and mold compound interfaces. The Fish-Bone Diagram has been generated to hypothesize potential root causes, to prove and disprove each hypothesis [29].

C, S and Nishant, (2025) Suggested Failure Mode and Effects Analysis (FMEA), a management method for ranking and identifying possible risk factors that could contribute to failures in a scientific manner six critical factors insufficient course materials, inefficient teaching methods, poor classroom environment, lack of opportunities for practical application, language barriers, and negative peer pressure. primary data collected. FMEA analysis takes into account Severity, Occurrence and Detection of each of the six factors and then ranks them by Risk Priority Number (RPN) [30].

Ahmad et al. (2024) suggested failure analysis (FA) is crucial in identifying the actual root cause of these failures technologies and packaging methods. Resolve failure recovery issues and efficiently identify the root causes of failure mechanisms. FA procedures for recoverable package leakages, critical evidence might be missed, leading to inaccurate begins with electrical characterization to identify anomalies, fault isolation to pinpoint the fault. failure mechanism, ensuring no potential cause that enhances the identification of device failure mechanism recovery issues are addressed effectively, providing the production team with precise insights into the failure mechanisms and facilitating accurate investigations [31].

Purra et al. (2024) study mechanical and electrical failures, specifically with overhanging dies. The encapsulated package with visible surface defects is taken for the study to understand the root cause of the defects. Decapsulation of packages have visible die cracks and simulations are performed to understand the effect of the package development failure mode of fluid structure interaction (FSI) during encapsulation is simulated and understood the effect of mold flow on the overhang [32].

Berladir et al. (2024) In order to employ root cause analysis to meet the specific materials science objective of discovering and fixing the underlying causes of issues or events, a destroyed component of the petrol pumping unit's exhaust tract was chosen to ascertain the reasons for its failure. The second phase of data collection was the failure analytics of a destroyed element, the identification of as many causative variables as possible using a mnemonic known as the 6Ms of production, a detailed analysis of the causal factors, and the determination of the root causes [33]

TABLE IV. COMPARATIVE ANALYSIS OF LITERATURE ON ROOT CAUSE ANALYSIS TECHNIQUES FOR MECHANICAL FAILURES

Author (Year)	Study Focus	Key Finding	Challenges	Limitations	Future Work
Pinto (2026)	Reliability analysis of air-start system	Leakage and contamination reduced system reliability (MTBF 112 h)	Single-point failures	Subsystem-specific study	Improve sealing and redundancy design
Chai et al. (2025)	Delamination in semiconductor packaging	Thermal stress caused severe interface delamination	Stress-induced interface weakness	Packaging-focused scope	Enhance material interface strength
C., S., & Nishant (2025)	FMEA-based risk assessment	Ranked six critical risk factors using RPN	Quantifying qualitative risks	Context-specific data	Develop predictive FMEA models
Ahmad et al. (2024)	Failure analysis of package leakage	Electrical FA improved root cause detection	Evidence loss during recovery	Limited to leakage cases	Automate fault isolation process
Purra et al. (2024)	Overhanging die failure analysis	Mold flow induced die cracking	FSI complexity	Simulation-dependent results	Optimize encapsulation design
Berladir et al. (2024)	RCA of gas pumping exhaust failure	6Ms method identified multi-factor causes	Complex multi-causal factors	Case-specific analysis	Integrate material degradation modeling

VI. CONCLUSION AND FUTURE WORK

Root Cause Analysis (RCA) methods in mechanical failure analysis and insisted on the need of a more systematic and evidence-based thinking in engineering practice. Mechanical failures are hardly caused by individual component defects; they are manifested through interacting material, operating, design, and organizational factors, through which successful failure investigation necessitates logical structuring of causes, technical substantiation, and quantitative reliability evaluation. The hierarchy of causation models and reliability metrics allow engineers to make sure that corrective measures are taken against underlying deficiencies, as opposed to the symptoms of failure. The analysis also reveals that the success of RCA lies in integrating methodologies of diagnostic tools, probabilistic modeling and systems-level assessment in one framework. This kind of integration gives more power to technical decision-making and improves long-term operational stability. Further research should investigate the development of adaptive and hybrid RCA models that integrate real-time monitoring data with high-level computational analytics. The combination of machine learning, digital twin environments, and predictive reliability modelling provide good prospects of making a shift between failure response and failure prevention. Standardization of investigation procedures in industries will also help in enhancing the performance of mechanical systems in terms of consistency, transparency, and reliability.

REFERENCES

[1] S. Woo, "Mechanical System Failures," in *Reliability Design of Mechanical Systems: A Guide for Mechanical and Civil Engineers*, Singapore: Springer Singapore, 2020, pp. 249–306. doi: 10.1007/978-981-13-7236-0_7.

[2] S. R. Browd, B. T. Ragel, O. N. Gottfried, and J. R. W. Kestle, "Failure of Cerebrospinal Fluid Shunts: Part I: Obstruction and Mechanical Failure," *Pediatr. Neurol.*, vol. 34, no. 2, pp. 83–92, Feb. 2006, doi: 10.1016/j.pediatrneurol.2005.05.020.

[3] E. O. Ogunnowo, M. A. Adewoyin, J. E. Fiemotongha, and T. O. Igunma, "Systematic Review of Non-Destructive Testing Methods for Predictive Failure Analysis in Mechanical Systems," *IRE Journals*, vol. 4, no. 4, October, pp. 207–222, 2020.

[4] R. Patel and P. B. Patel, "A Review on Mechanical System Reliability & Maintenance strategies for Maximizing Equipment Lifespan," *ESP J. Eng. Technol. Adv.*, vol. 2, no. 1, pp. 173–179, 2022, doi: 10.56472/25832646/JETA-V2I1P120.

[5] R. Ursprung and J. Gray, "Random Safety Auditing, Root Cause Analysis, Failure Mode and Effects Analysis," *Clin. Perinatol.*, vol. 37, no. 1, pp. 141–165, Mar. 2010, doi: 10.1016/j.clp.2010.01.008.

[6] J. Soldani and A. Brogi, "Anomaly Detection and Failure Root Cause Analysis in (Micro) Service-Based Cloud Applications: A Survey," *ACM Comput. Surv.*, vol. 55, no. 3, Feb. 2022, doi: 10.1145/3501297.

[7] N. Prajapati, "Machine Learning-Based Efficiency Prediction of Computer Systems Based on Various Hardware Fault Configurations," in *2025 International Conference on Information, Implementation, and Innovation in Technology (I2ITCON)*, 2025, pp. 1–6. doi: 10.1109/I2ITCON65200.2025.11210520.

[8] R. Patel and P. B Patel, "The Role of Simulation & Engineering Software in Optimizing Mechanical System Performance," *Tech. Int. J. Eng. Res.*, vol. 11, no. 6, pp. 991–996, 2024, doi: 10.56975/tijer.v11i6.158468.

[9] Q. Zhang, C. Hua, and G. Xu, "A mixture Weibull proportional hazard model for mechanical system failure prediction utilising lifetime and monitoring data," *Mech. Syst. Signal Process.*, vol. 43, no. 1–2, pp. 103–112, Feb. 2014, doi: 10.1016/j.ymssp.2013.10.013.

[10] P. Martin, J. E. Strutt, and N. Kinkead, "A review of mechanical reliability modelling in relation to failure mechanisms," *Reliab. Eng.*, vol. 6, no. 1, pp. 13–42, Jan. 1983, doi: 10.1016/0143-8174(83)90029-X.

[11] V. Sanikal, "Battery Degradation Forecasting with FMU and Optimization Framework Using Synthetic Generated Data," *Int. J. Emerg. Res. Eng. Technol.*, vol. 6, no. 4, pp. 48–55, 2025, doi: 10.63282/3050-922x.ijeret-v6i4p106.

[12] W. M. Goble and J. V Bukowski, "Development of a Mechanical Component Failure Database," in *2007 Annual Reliability and Maintainability Symposium*, 2007, pp. 451–455. doi: 10.1109/RAMS.2007.328112.

[13] P. M. Williams, "Techniques for Root Cause Analysis," *Baylor Univ. Med. Cent. Proc.*, vol. 14, no. 2, pp. 154–157, 2001, doi: 10.1080/08998280.2001.11927753.

[14] D. Mahto and A. Kumar, "Application of root cause analysis in improvement of product quality and productivity," *J. Ind. Eng. Manag.*, vol. 1, no. 2, pp. 16–53, 2008, doi: 10.3926/jiem.2008.v1n2.p16-53.

[15] P. Viveros, E. Zio, C. Nikulin, R. Stegmaier, and G. Bravo, "Resolving equipment failure causes by root cause analysis and theory of inventive problem solving," *Proc. Inst. Mech. Eng. Part O J. Risk Reliab.*, vol. 228, no. 1, pp. 93–111, Feb. 2013, doi: 10.1177/1748006X13494775.

[16] V. Sanikal, "Real-Time Energy and Thermal Optimization in Electric Delivery Fleets via Edge-Based Forecasting and Deep Q-Learning," *Int. J. Artif. Intell. Data Sci. Mach. Learn.*, vol. 7, no. 1, pp. 183–188, 2026, doi: 10.63282/3050-9262.IJAIDSML-V7I1P131.

[17] V. Thakran, "Impact of Advanced Materials in Enhancing the Mechanical Properties of Piping Systems for Stress Analysis," *Int. J. Recent Technol. Sci. Manag.*, vol. 7, no. 4, pp. 66–74, 2022.

[18] R. Suresh, A. Sivaram, and V. Venkatasubramanian, "A hierarchical approach for causal modeling of process systems,"

Comput. Chem. Eng., vol. 123, pp. 170–183, Apr. 2019, doi: 10.1016/j.compchemeng.2018.12.017.

[19] S. B. R. Karri, V. K. Devalla, R. K. Bojja, and M. S. Pandey, "An Architecture for Model Monitoring System with Automated Data Validation and Failure Handling," in *2025 3rd International Conference on Communication, Security, and Artificial Intelligence (ICCSAI)*, IEEE, Apr. 2025, pp. 1960–1966. doi: 10.1109/ICCSAI64074.2025.11064092.

[20] T. Chu, T. Nguyen, H. Yoo, and J. Wang, "A review of vibration analysis and its applications," *Heliyon*, vol. 10, no. 5, Mar. 2024, doi: 10.1016/j.heliyon.2024.e26282.

[21] V. Thakran, "Intelligent Modelling of Pressure Loss Estimation in Emulsion Pipelines Using Machine Learning Techniques," in *2025 International Conference on Electrical, Electronics, and Computer Science with Advance Power Technologies - A Future Trends (ICE2CPT)*, IEEE, Oct. 2025, pp. 1–6. doi: 10.1109/ICE2CPT66440.2025.11340245.

[22] R. Patel and P. Patel, "Machine Learning-Driven Predictive Maintenance for Early Fault Prediction and Detection in Smart Manufacturing Systems," *ESP J. Eng. Technol. Adv.*, vol. 4, no. 1, 2024, doi: 10.56472/25832646/JETA-V4I1P120.

[23] R. Patel, "Predictive Analytics for Assessing the Efficiency of Ground-Source Heat Pumps under Thermal Interference Based on Machine Learning Models," in *2025 International Conference on Smart & Sustainable Technology (INCSST)*, 2025, pp. 1–6. doi: 10.1109/INCSST64791.2025.11210249.

[24] R. Kalantarpour and K. Vafai, "Advancements in data center thermal management," in *International Journal of Research and Analytical Reviews*, vol. 8, no. 2, 2024, pp. 39–80. doi: 10.1016/bs.aiht.2024.07.002.

[25] S. Engineering, "Advances in finite element analysis for computational mechanics 2015," *SAGE J.*, vol. 7, no. 7, pp. 1–2, 2015, doi: 10.1177/1687814015595739.

[26] V. Thakran, "Utilization of Machine Learning Algorithms in Optimizing Finite Element Modeling and Analysis," in *2025 International Conference on Smart & Sustainable Technology (INCSST)*, 2025, pp. 1–6. doi: 10.1109/INCSST64791.2025.11210352.

[27] I. ul Hassan, K. Panduru, and P. J. Walsh, "Non-destructive testing methods for condition monitoring: A review of techniques and tools," *Procedia Comput. Sci.*, vol. 257, pp. 420–427, 2025, doi: 10.1016/j.procs.2025.03.055.

[28] G. P. M. Pinto, "Root-Cause Investigation and Technical Reliability Analysis of the Starting-Air System Failure in a Marine Generator A Case Study of KM Sabuk Nusantara 101," *G-Tech J. Teknol. Terap.*, vol. 10, no. 1, pp. 226–237, Jan. 2026, doi: 10.70609/g-tech.v10i1.8716.

[29] M. L. Chai, W. K. K. Thong, S. C. C. Lee, J. Lim, and D. K. P. Meng, "Delamination Root Cause Analysis in Leaded Package," in *2025 IEEE 27th Electronics Packaging Technology Conference (EPTC)*, 2025, pp. 1–7. doi: 10.1109/EPTC67330.2025.11392641.

[30] I. C, B. S, and N. Nishant, "A Study on Utilizing Failure Mode and Effects Analysis (FMEA) to Identify Root Causes Contributing to Student Learning Failures in an Academic Environment," in *2025 3rd International Conference on Advancements in Electrical, Electronics, Communication, Computing and Automation (ICAECA)*, 2025, pp. 1–4. doi: 10.1109/ICAECA63854.2025.11012426.

[31] I. H. Ahmad, N. I. M. Arifen, M. E. Bin Rosle, and M. F. Bin Mohamad, "Identification of Recovering Package Leakage Failure Mode Via Novel Comprehensive Failure Analysis Technique," in *2024 IEEE International Symposium on the Physical and Failure Analysis of Integrated Circuits (IPFA)*, IEEE, Jul. 2024, pp. 1–8. doi: 10.1109/IPFA61654.2024.10691207.

[32] A. R. Purra, H. Kumar, V. R. S. P. Vempaty, K. Tamala, and W. H. Sim, "Root cause analysis to predict the die cracks in the multichip package," in *2024 IEEE Electrical Design of Advanced Packaging and Systems (EDAPS)*, 2024, pp. 1–3. doi: 10.1109/EDAPS64431.2024.10988468.

[33] K. Berladir, T. Hovorun, J. Trojanowska, V. Ivanov, and A. Iakovets, "Failure Analytics of Defects in Mechanical Engineering Parts Using Root Cause Analysis: Case Study," in *Springer*, 2024, pp. 328–341.

