A Project Report on

"AI Based Predictive Maintenance and Structural Health Monitoring of ATAGS Guns"

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CERTIFICATE OF COMPLETION

OF INTERNSHIP

Armament Research and Development Establishment, DRDO

This is to certify that Ms. **Wagh Shrutika Suryabhan** with **MIS No. 64210020** has successfully completed her **Internship** at **Armament Research and Development Establishment, DRDO** during the period of **1st June to 31st December 2025.** During this period, she has worked on the project titled **"AI Based Predictive Maintenance and Structural Health Monitoring of ATAGS Guns"** under the guidance of Dr. Dr. Harneet V Thakur.

Signature	**Signature**
Dr. Harneet V Thakur (Sc.G)	**Mr. Rounak Padgil (Sc.E)**

<u>ACKNOWLEDGEMENT</u>

It is indeed a matter of great pleasure and privilege to be able to present this report on **"AI Based Predictive Maintenance and Structural Health Monitoring of ATAGS Guns"**. I am very grateful and would like to appreciate all the people who helped me to complete my training as the knowledge I gained during this period was immense. I also offer a very special thanks to **Armament Research and Development Establishment, DRDO** for giving me such a golden opportunity of grateful stay in its industry as an intern.

I am sincerely thankful to my guide **Dr. Harneet V. Thakur** for her valuable guidance and continuous encouragement throughout this project. I also express my sincere gratitude to **Mr. Rounak Padgil** and **Mr. Subhash** for their significant support, technical assistance, and helpful guidance during the course of this work. I extend my heartfelt thanks to my teammates **Yugandhar, Manas, Sanskruti, Amit**, and **Pragyunsh** for their constant encouragement, meaningful technical discussions, and cooperative support, which greatly contributed to the successful completion of this project.

Last but not the least I would like to thank, I also wish to acknowledge my indebtedness to the **staff of ARDE** without whose cooperation, this training would not have been successful.

DECLARATION

I hereby declare that this project work entitled **"AI Based Predictive Maintenance and Structural Health Monitoring of ATAGS Guns"** submitted by me is an authentic record of my own work carried out at **Armament Research and Development Establishment, DRDO** under the guidance of **Dr. Harneet V Thakur (Sc.G)** during **1st June to 31st December, 2025.**

Wagh Shrutika Suryabhan.

Place: Pune.

Date:

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CHAPTER 2

2.1 INTRODUCTION ABOUT THE ORGANISATION

The **Defence Research and Development Organisation (DRDO)** is the premier agency under the **Ministry of Defence, Government of India**, responsible for designing, developing, and delivering state-of-the-art defence technologies, weapon systems, sensors, and equipment for the Indian Armed Forces. Established in **1958**, DRDO began as a small organisation formed by merging the Technical Development Establishments (TDEs), the Directorate of Technical Development and Production (DTDP), and the Defence Science Organisation (DSO). Since then, it has evolved into one of the largest defence R&D networks in the world.

DRDO operates with the motto **"Balasya Mulam Vigyanam"** meaning *"Strength's Origin is in Science."* Its vision is to build a strong, self-reliant India in the field of defence through indigenous research, innovation, and technology development. Over the years, DRDO has expanded into a network of over **50 laboratories, centres, and establishments**, covering almost every major discipline in defence technology—ranging from aeronautics, missiles, combat vehicles, electronics, radars, naval systems, cyber technologies, materials engineering, life sciences, armaments, AI, and unmanned systems.

A major objective of DRDO is enabling **technological self-reliance** and reducing the country's dependency on foreign defence imports. To achieve this, DRDO undertakes the complete development cycle: fundamental research, concept design, prototype development, field testing, user trials, and technology transfer for mass production. It works closely with DPSUs, Ordnance Factories, private industry, MSMEs, and academia to strengthen the defence manufacturing ecosystem.

DRDO has been responsible for several milestone achievements such as the Integrated Guided Missile Development Programme (AGNI, PRITHVI, AKASH, NAG), AEW&C platforms, advanced radars, electronic warfare systems, combat vehicles like Arjun MBT, torpedoes, UAVs, explosive detection systems, and protective technologies for soldiers. DRDO's contributions have significantly enhanced the operational readiness and strategic capabilities of India's armed forces.

The organisation also plays a crucial role in international collaborations, export-ready defence technologies, and long-term R&D roadmaps for future warfare—covering directed energy systems, hypersonics, robotics, AI-enabled combat systems, advanced propulsion, and next-generation sensors. Through continuous innovation and scientific expertise, DRDO stands as the backbone of India's defence preparedness.

2.2. Vision, Mission & Objectives

Vision

To empower the nation with cutting-edge defence technologies and make India self-reliant in strategic systems.

Mission

- To design, develop and deliver state-of-the-art weapon systems, sensors, platforms, electronics and materials.

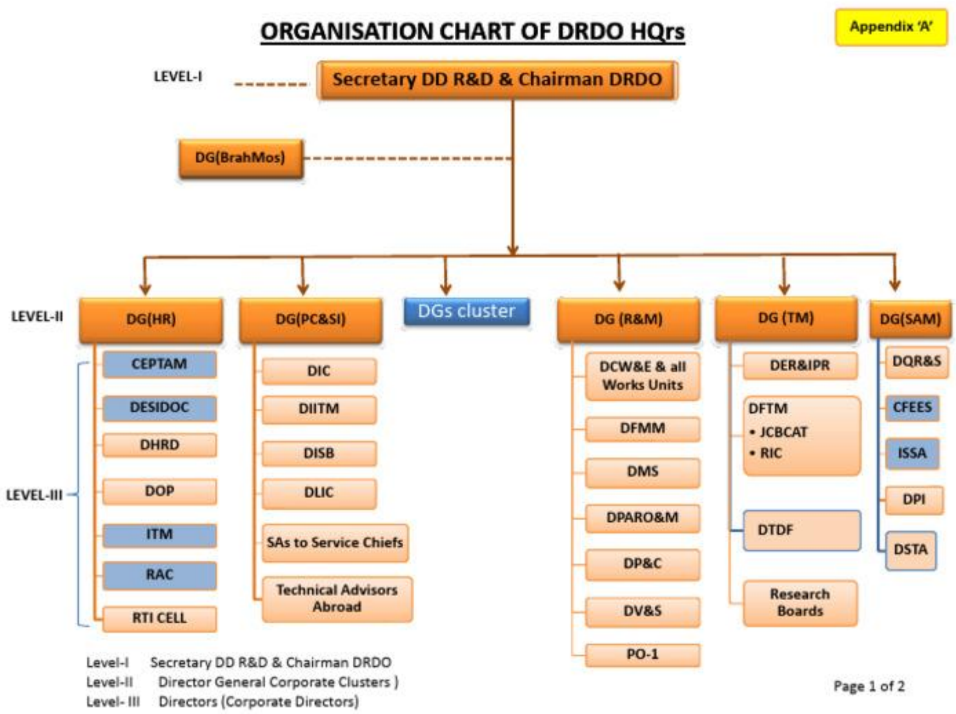
- To create a strong ecosystem of defence manufacturing with transfer-of-technology (ToT) to public and private industries.
- To support the Indian Armed Forces through upgrades, testing, certification and technical consultancy.

Core Objectives

1. Conduct advanced and applied research in critical defence domains.
2. Develop prototypes through system-level engineering.
3. Perform full-scale trials, evaluation and environmental testing.
4. Indigenize components, materials and subsystems.
5. Enable large-scale production through industry partnerships.
6. Maintain long-term technology roadmaps for future warfare.

2.3. Organisational Structure of DRDO

The organisational structure of the Defence Research and Development Organisation (DRDO) is designed to provide centralized leadership at the headquarters level while enabling decentralised execution through technology-domain-based laboratories. The structure shown in the figure represents the administrative and technical hierarchy of DRDO, consisting of three major levels: apex leadership, corporate/functional directorates, and technology domain clusters.



2.3.1 Level I

At **Level I**, DRDO is headed by the **Secretary, Department of Defence Research and Development (DDR&D) and Chairman, DRDO**. This position represents the highest authority in the organisation and is responsible for overall policy formulation, strategic planning, approval of major defence R&D programmes, and coordination with the Ministry of Defence and the Armed Forces. The Chairman ensures alignment of DRDO's research objectives with national security requirements. The **Director General (BrahMos)** functions directly under the Chairman due to the strategic importance of the BrahMos missile programme.

2.3.2 Level II – Corporate and Functional Director Generals

At **Level II**, DRDO headquarters functions through multiple **Director Generals (DGs)** who head corporate and functional domains. These DGs are responsible for policy implementation, administrative control, and technical oversight across the organisation.

The major corporate Director Generals include:

1. **DG (HR)**, responsible for human resource management, recruitment, training, promotions, and personnel policies. This DG oversees directorates such as CEPTAM, DESIDOC, HRD, ITM, RAC, and RTI Cell.
2. **DG (Planning & Coordination and Services Interaction – PC&SI)**, responsible for long-term planning, inter-services coordination, international cooperation, and liaison with service headquarters. This includes directorates such as DIC, DITM, DISB, DLIC, and Service Advisors.
3. **DG (R&M)**, responsible for research management, quality assurance, safety, reliability, documentation, and project monitoring. This DG oversees directorates handling evaluation, documentation, project audits, and vigilance.
4. **DG (Technology Management – TM)**, responsible for technology development, technology transfer, intellectual property management, and research boards. This includes directorates such as DER&IPR, DFTM, JCB-CAT, RIC, and DTDF.
5. **DG (SAM)**, responsible for scientific advisory mechanisms, systems analysis, evaluation studies, and performance audits.

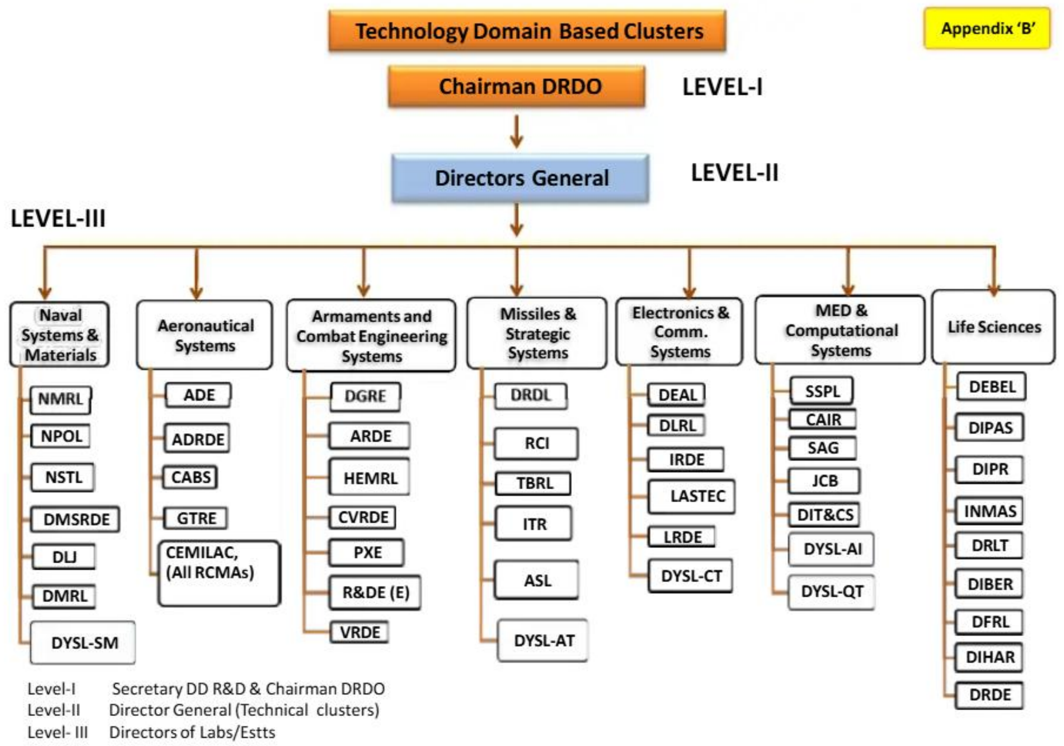
These DGs ensure effective governance, planning, quality control, and administrative support for all DRDO laboratories and projects.

2.3.3 Level III – Directors (Corporate Directorates)

At **Level III**, various **Directors** head individual corporate directorates under the respective DGs. These directorates execute specific functional responsibilities such as recruitment, documentation, technology forecasting, safety, finance coordination, and research grants. This level forms the operational backbone of DRDO headquarters and supports laboratory-level R&D activities.

Technology Domain Based Cluster Structure

In addition to the headquarters structure, DRDO follows a **technology-domain-based cluster system** to manage its laboratories effectively. This structure ensures focused development in specialised defence technology areas while maintaining technical coordination.



At **Level I**, the **Chairman, DRDO** provides overall leadership and direction.

At **Level II**, **Directors General (Clusters)** are responsible for supervising laboratories grouped under specific technology domains. These DGs provide technical guidance, review progress, and ensure integration among laboratories within the same domain.

At **Level III**, individual **laboratories and establishments** function under these clusters. Each laboratory is headed by a Director and is responsible for design, development, testing, and validation of systems within its assigned domain.

The major technology domain clusters include:

1. **Naval Systems and Materials**, covering underwater systems, naval sensors, and materials research.
2. **Aeronautical Systems**, focusing on aircraft, UAVs, flight control systems, and airborne sensors.
3. **Armaments and Combat Engineering Systems**, dealing with weapons, ammunition, explosives, and combat vehicles.

4. **Missiles and Strategic Systems**, responsible for missile systems, launch vehicles, and strategic technologies.
5. **Electronics and Communication Systems**, covering radars, electronic warfare, communication, and sensor technologies.
6. **Microelectronics and Computational Systems**, focusing on AI, computing, embedded systems, and cyber technologies.
7. **Life Sciences**, responsible for biomedical, physiological, and soldier-support technologies.

Each cluster consists of multiple specialised laboratories working collaboratively under a common technical leadership.

2.4 Products of DRDO

The Defence Research and Development Organisation (DRDO) has developed a wide range of defence products and technologies to meet the operational requirements of the Indian Armed Forces. These products span strategic systems, combat platforms, weapons, sensors, electronic warfare systems, naval systems, and soldier-support equipment. DRDO products are designed, developed, tested, and validated indigenously and are inducted into service through collaboration with production agencies and industry partners.

2.4.1. Missile Systems

DRDO has played a key role in establishing India's indigenous missile capability. These systems provide strategic deterrence, air defence, and precision strike capabilities.

Major missile products include:

1. Agni series – Long-range ballistic missiles for strategic deterrence
2. Prithvi series – Short-range surface-to-surface missiles
3. Akash – Surface-to-air missile system for air defence
4. Astra – Beyond-visual-range air-to-air missile
5. Nag / Helina – Anti-tank guided missile systems
6. BrahMos – Supersonic cruise missile (jointly developed)
7. QRSAM / MRSAM – Quick reaction and medium-range air defence systems

2.4.2. Aeronautical Systems and Aircraft

DRDO has developed several aeronautical platforms and subsystems to enhance air combat, surveillance, and unmanned capabilities.

Key aeronautical products include:

1. LCA Tejas – Indigenous light combat aircraft
2. Light Combat Helicopter (LCH)
3. AEW&C – Airborne Early Warning and Control system
4. TAPAS / Rustom UAVs – Medium-altitude long-endurance UAVs
5. Flight control systems and avionics for aircraft and UAVs

2.4.3. Armament and Combat Engineering Systems

DRDO has developed a range of weapons, ammunition, artillery systems, and combat vehicles for land warfare.

Major products include:

1. Arjun Main Battle Tank (MBT)
2. Pinaka Multi-Barrel Rocket Launcher
3. Advanced towed artillery gun systems
4. Small arms and infantry weapon systems
5. Artillery, tank, and mortar ammunition
6. Fuzes, warheads, and explosive devices

2.4.4. Electronic Warfare, Radar and Sensor Systems

DRDO has developed advanced radars and electronic warfare systems for surveillance, target detection, and threat neutralisation.

Key products include:

1. Rohini and Revathi radars
2. Arudhra Medium Power Radar
3. Battlefield surveillance radars
4. Naval and airborne surveillance radars
5. Electronic warfare suites for aircraft, ships, and ground systems

2.4.5. Naval Systems and Underwater Technologies

DRDO supports naval operations through indigenous underwater weapons, sensors, and materials.

Major naval products include:

1. Varunastra Heavy Weight Torpedo
2. Underwater sonar systems
3. Mine countermeasure systems
4. Submarine rescue and detection systems
5. Stealth materials and naval coatings

2.4.6. Microelectronics, AI and Computational Systems

DRDO has developed indigenous computing, artificial intelligence, and embedded systems to support modern warfare.

Key products include:

1. Mission computers and embedded systems
2. Artificial intelligence-based decision support tools
3. Secure communication and data processing systems
4. Autonomous and robotic platforms

2.4.7. Life Sciences and Soldier Support Systems

DRDO develops systems to enhance soldier survivability, health, and performance in extreme operational conditions.

Major products include:

1. High-altitude and special ration packs
2. Protective clothing and NBC suits
3. Respiratory protection systems
4. Biomedical equipment for battlefield use
5. CBRN detection and protection systems

2.4.8. Dual-Use and Civilian Applications

Several DRDO technologies have civilian and dual-use applications.

Examples include:

1. Disaster management and detection systems
2. Medical equipment and protective gear
3. Advanced materials and sensors
4. COVID-19 medical and safety technologies

2.5 About Armament Research and Development Establishment (ARDE)

The Armament Research and Development Establishment (ARDE) is one of the premier laboratories of the Defence Research and Development Organisation (DRDO), functioning under the Armament and Combat Engineering Systems cluster. ARDE is located in Pune, Maharashtra, and was established in 1958. The laboratory is responsible for the design, development, and evaluation of conventional armament systems required by the Indian Armed Forces. ARDE plays a crucial role in strengthening indigenous capability in weapons, ammunition, explosives, and related technologies.

ARDE’s primary mandate is to undertake end-to-end development of armament systems, starting from concept formulation and detailed design to prototype development, testing, validation, and transfer of technology to production agencies. The laboratory works in close coordination with user services, quality assurance agencies, and manufacturing partners to ensure that developed systems meet operational, safety, and reliability requirements.

2.5.1 Role and Responsibilities of ARDE

ARDE is responsible for the development of a wide range of armament systems for land, air, and naval applications. The laboratory focuses on improving lethality, accuracy, safety, reliability, and service life of weapon systems while ensuring compliance with military standards.

Major responsibilities include:

- Design and development of guns, ammunition, and infantry weapon systems
- Development of warheads, fuzes, and explosive devices
- Structural and thermal analysis of armament components
- Safety, reliability, and life-assessment studies
- User trials, environmental testing, and validation
- Technology transfer to production agencies

2.5.2 Organisational Structure of ARDE

ARDE functions under the administrative and technical control of DRDO headquarters. The laboratory is headed by a Director, who is responsible for overall management and technical leadership. The Director is supported by Associate Directors, Group Directors, and Division Heads, each overseeing specialised technical domains.

Internal organisational structure includes:

- Director
- Associate Director(s)
- Group / Division Heads
- Project Leaders
- Scientists, Engineers, and Technical Staff

The laboratory follows a project-based execution model, where multidisciplinary teams are formed for specific armament development programmes.

2.5.3 Major Product Areas of ARDE

ARDE develops a broad spectrum of armament products that support the operational needs of the Indian Army, Navy, and Air Force.

1. Guns and Artillery Systems

- Components and subsystems for artillery guns
- Recoil systems, breech mechanisms, and mounting structures

2. Ammunition Systems

- Artillery ammunition
- Tank and mortar ammunition
- Practice, training, and special-purpose ammunition

3. Infantry Weapons

- Small arms and weapon subsystems
- Accessories and support equipment

4. Warheads and Explosives

- High-explosive and shaped-charge warheads
- Explosive cartridges and pyrotechnic devices
- Insensitive munition technologies

5. Fuzes and Safety Mechanisms

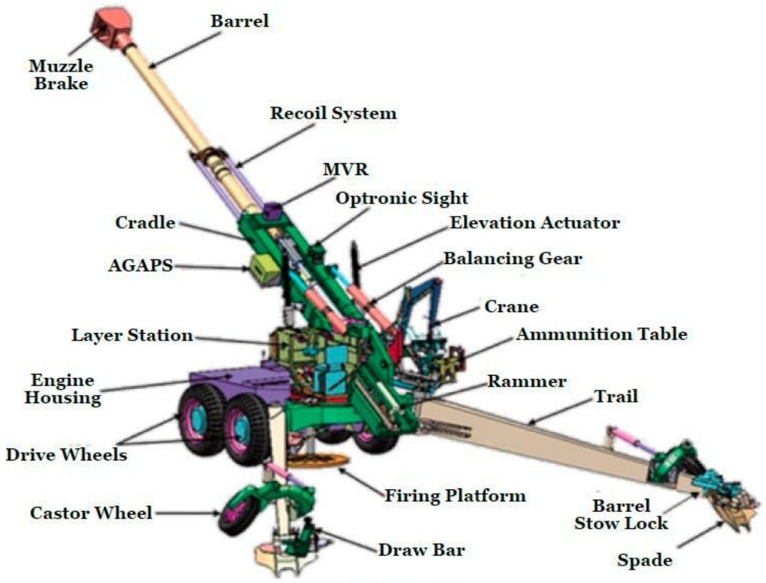
- Mechanical and electronic fuzes
- Safety and arming devices
- Initiation systems

2.5.4 Achievements and Contributions

ARDE has made significant contributions to India's defence preparedness by enabling indigenous development of critical armament technologies.

Key achievements include:

- Development of indigenous artillery and ammunition systems
- Contribution to Pinaka rocket system components
- Indigenous development of fuzes and warheads
- Support for indigenisation and import substitution programmes
- Successful transfer of technologies to Ordnance Factories and private industry



ATAGS Schematic

CHAPTER 3

INTRODUCTION TO PROECT

3.1 Problem statement

The Advanced Towed Artillery Gun System (ATAGS) operates under severe dynamic and cyclic loading conditions due to repeated firing, recoil forces, transportation, and environmental exposure. These operational conditions induce vibrations, stresses, and fatigue in critical structural components, which can lead to gradual degradation, loss of stiffness, and potential structural failures if not detected at an early stage. Conventional maintenance practices for artillery systems are largely time-based or inspection-driven, making them inadequate for early fault detection and real-time health assessment.

Existing maintenance approaches lack continuous monitoring capability and do not effectively capture changes in dynamic characteristics such as natural frequencies, mode shapes, and deformation patterns. Variations in these parameters are strong indicators of structural damage, looseness, material degradation, or boundary condition changes. However, these indicators are not systematically utilised in current maintenance frameworks for ATAGS.

Furthermore, the absence of an integrated structural health monitoring system limits the ability to correlate analytical predictions with actual operational behaviour. Without validated modal characteristics and optimised sensor placement, reliable condition-based maintenance and damage prediction remain challenging. Manual interpretation of vibration data is also time-consuming and prone to subjectivity, reducing the effectiveness of maintenance decision-making.

Therefore, there is a critical need for a predictive maintenance framework that integrates finite element analysis, modal analysis, sensor-based vibration monitoring, and artificial intelligence techniques. Such a system should be capable of identifying deviations in modal parameters, localising structural deformation, optimising sensor selection and placement, and analysing large volumes of vibration data for early damage detection.

The problem addressed in this project is the development of an AI-based predictive maintenance and structural health monitoring methodology for the ATAGS gun system that can continuously assess structural integrity, detect anomalies at an early stage, and support informed maintenance decisions. The solution aims to enhance operational reliability, improve safety, reduce unplanned downtime, and extend the service life of the ATAGS gun system.

3.2 About ATAGS

The Advanced Towed Artillery Gun System (ATAGS) is an indigenously designed and developed 155 mm/52 calibre artillery gun system developed under the aegis of the Defence Research and Development Organisation (DRDO) for the Indian Army. ATAGS represents a major milestone in India's artillery modernisation programme and aims to replace legacy artillery systems with a high-performance, long-range, and technologically advanced gun system.

ATAGS has been developed through a collaborative effort involving DRDO laboratories—primarily ARDE, along with other DRDO establishments—and Indian defence industry partners. The system is designed to meet contemporary battlefield requirements, including long-range firepower, high accuracy, rapid deployment, and sustained firing capability under extreme operational conditions.

3.2.1 Design and Technical Features

ATAGS is designed as a towed artillery system with advanced structural, mechanical, and electronic features to enhance performance and reliability. The system incorporates modern materials, robust structural design, and automated subsystems to improve firing efficiency and crew safety.

3.2.2 Key technical features include:

- 155 mm calibre gun with 52-calibre barrel length
- Long firing range with extended range ammunition
- High chamber pressure capability for enhanced performance
- Automated ammunition handling and loading assistance
- Advanced recoil management and braking systems
- Integrated fire control and navigation systems

The gun structure is designed to withstand repeated high-energy firing loads, recoil forces, and dynamic stresses during operation and transportation.

3.2.3 Operational Capabilities

ATAGS offers improved operational flexibility and battlefield effectiveness compared to legacy artillery systems. It is capable of delivering sustained and intense firepower while maintaining accuracy and structural integrity.

Operational capabilities include:

- Long-range artillery fire with high accuracy
- Rapid deployment and repositioning
- Capability to operate in diverse terrains and climatic conditions
- Sustained firing rates with controlled thermal and structural response
- Compatibility with modern artillery ammunition types

These capabilities make ATAGS suitable for both conventional and high-intensity conflict scenarios.

3.2.4 Structural and Dynamic Considerations

The ATAGS gun system experiences significant dynamic loading due to firing recoil, barrel vibrations, structural resonance, and transportation-induced excitations. Repeated firing cycles introduce fatigue stresses in critical components such as the barrel assembly, breech mechanism, cradle, trails, and mounting structures.

Key structural challenges include:

- High-frequency vibrations during firing
- Dynamic deformation of gun components
- Fatigue damage due to cyclic loading
- Sensitivity of structural response to boundary conditions
- Long-term degradation affecting accuracy and safety

These factors necessitate detailed structural analysis and continuous monitoring to ensure long-term reliability.

3.3 About Structural Health Monitoring and Predictive Maintenance

Structural Health Monitoring (SHM) is a systematic approach for the continuous or periodic assessment of the integrity, performance, and safety of engineering structures. It involves the acquisition, processing, and interpretation of data obtained from sensors mounted on critical structural components. The primary objective of SHM is to detect damage at an early stage by identifying changes in structural behaviour such as stiffness degradation, mass variation, and altered dynamic response.

Predictive Maintenance is an advanced maintenance strategy that uses monitored data, analytical models, and data-driven algorithms to predict the future condition of a system. Unlike traditional time-based or reactive maintenance approaches, predictive maintenance enables maintenance actions to be scheduled based on the actual health condition of the structure, thereby improving reliability and reducing unnecessary downtime.

3.3.1 Principle of Structural Health Monitoring

SHM is based on the premise that damage in a structure alters its physical properties, which in turn affects its dynamic characteristics. Parameters such as natural frequencies, mode shapes, damping ratios, and deformation patterns are highly sensitive to changes in structural integrity.

Key principles include:

- Monitoring dynamic response under operational or ambient excitations
- Identifying deviations from baseline structural behaviour
- Correlating analytical and experimental modal parameters
- Localising and quantifying damage using response signatures

Modal analysis plays a crucial role in SHM, as changes in modal frequencies and mode shapes serve as reliable indicators of structural degradation.

3.3.2 Components of an SHM System

An SHM system consists of both hardware and software elements working in an integrated manner to assess structural condition.

Major components include:

- Sensors such as accelerometers, strain gauges, and vibration transducers
- Data acquisition systems for high-frequency signal recording
- Signal processing and feature extraction algorithms
- Analytical and numerical models for correlation
- Decision-making frameworks for damage assessment

The selection and placement of sensors are critical and are often guided by modal analysis results to ensure maximum sensitivity to damage-prone regions.

3.3.3 Predictive Maintenance Framework

Predictive maintenance extends SHM by incorporating prognostic capabilities that estimate the remaining useful life of structural components. It integrates historical data, real-time measurements, and predictive models to forecast future degradation trends.

Core elements of predictive maintenance include:

- Continuous condition monitoring
- Detection of abnormal trends and anomalies
- Comparison of measured and model-based responses
- Prediction of failure onset or performance degradation
- Optimised maintenance scheduling

Artificial intelligence and machine learning techniques enhance predictive maintenance by enabling automated pattern recognition and adaptive learning from large datasets.

3.3.4 Role of AI in SHM and Predictive Maintenance

AI-based methods enable efficient processing of complex and high-dimensional vibration data generated by SHM systems. Machine learning algorithms can identify subtle changes in modal parameters that may not be evident through conventional analysis.

Advantages of AI integration include:

- Automated anomaly detection
- Improved damage classification and localisation
- Reduction in human interpretation errors
- Real-time decision support
- Scalability for large and complex systems

AI-driven models improve prediction accuracy by continuously updating themselves as new data becomes available.

3.3.5 Benefits of SHM and Predictive Maintenance

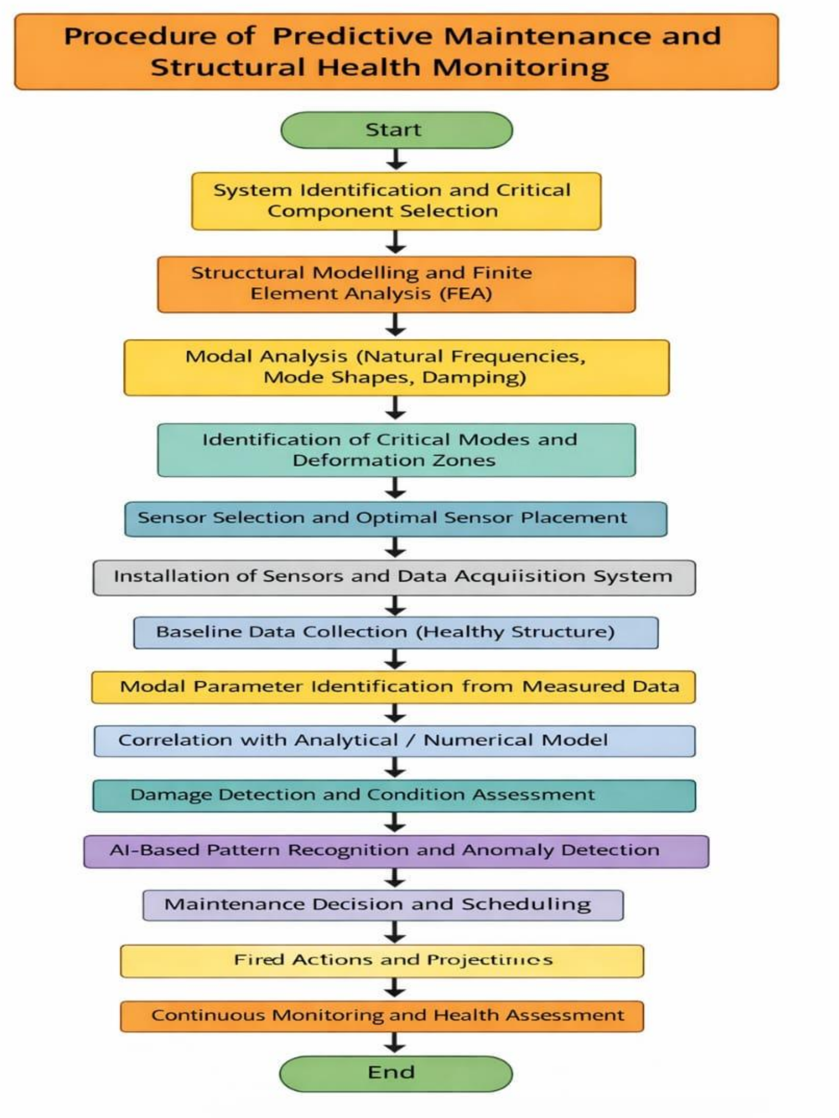
The adoption of SHM and predictive maintenance offers significant operational and economic advantages, particularly for high-value defence systems.

Key benefits include:

- Early damage detection and risk mitigation
- Enhanced operational safety
- Reduction in unplanned failures
- Optimised maintenance cost and downtime
- Extended service life of critical assets

These benefits are especially critical for artillery systems such as ATAGS, which operate under high dynamic loads and severe service conditions.

3.3.6 Procedure of Predictive Maintenance and Structural Health Monitoring



1. The procedure of predictive maintenance and structural health monitoring begins with system identification and critical component selection. In this stage, the overall

structure or system under study is defined, and components that are most susceptible to damage due to operational loads, vibrations, fatigue, or environmental conditions are identified. This ensures that monitoring efforts are focused on structurally and functionally critical regions.

2. Following this, structural modelling and finite element analysis (FEA) is carried out to understand the stress distribution, deformation behaviour, and dynamic response of the structure. A detailed numerical model is developed to simulate real operating conditions and loading scenarios. The FEA model provides a theoretical baseline for evaluating the structural behaviour.
3. The next step involves modal analysis, where the natural frequencies, mode shapes, and damping characteristics of the structure are determined. Modal analysis helps in understanding how the structure vibrates under dynamic excitation and identifies resonance-prone frequencies that are sensitive to structural damage or stiffness variation.
4. Based on the modal analysis results, critical modes and deformation zones are identified. These regions experience higher vibration amplitudes or deformation and are more likely to exhibit changes when damage occurs. Identifying these zones is essential for effective monitoring and damage detection.
5. Subsequently, sensor selection and optimal sensor placement are performed. Appropriate sensors such as accelerometers or strain gauges are selected based on frequency range, sensitivity, and environmental suitability. Sensors are placed at locations corresponding to critical modes and high deformation zones to maximise damage sensitivity and measurement accuracy.
6. Once sensor placement is finalised, installation of sensors and the data acquisition system is carried out. This step ensures reliable data collection during operational or test conditions. Proper calibration and signal integrity checks are performed to maintain data quality.
7. After installation, baseline data collection is conducted when the structure is in a healthy or undamaged condition. This baseline dataset serves as a reference for future comparisons and helps in identifying deviations caused by damage or degradation.
8. The acquired data is then processed for modal parameter identification from measured data. Experimental modal parameters such as frequencies, mode shapes, and damping ratios are extracted using signal processing and system identification techniques.
9. These experimentally obtained parameters are compared through correlation with analytical or numerical models. Any discrepancies between measured and predicted values indicate possible modelling errors or structural changes. Model updating may be carried out to improve correlation.
10. Following correlation, damage detection and condition assessment are performed by analysing changes in modal parameters and response characteristics. Shifts in natural frequencies, alterations in mode shapes, or increased damping may indicate the presence and severity of damage.
11. To enhance reliability and automation, AI-based pattern recognition and anomaly detection techniques are applied. Machine learning algorithms analyse large datasets to identify abnormal trends, classify damage patterns, and detect early-stage faults that may not be evident through conventional methods.
12. Based on the assessed structural condition, maintenance decisions and scheduling are carried out. Maintenance actions are planned according to the predicted health status rather than fixed time intervals, enabling condition-based maintenance.
13. The step labelled fired actions and projectiles represents the structure operating under actual service conditions, such as repeated firing cycles in artillery systems. Data from

real operational events further enriches the monitoring system and improves prediction accuracy.

14. Finally, continuous monitoring and health assessment ensures that the system is repeatedly evaluated throughout its service life. The predictive maintenance loop continues with updated data, refined models, and improved decision-making until the end of the operational cycle.

3.3.7 Applications of Predictive Maintenance and Structural Health Monitoring

Predictive maintenance and structural health monitoring are widely applied in engineering systems where structural integrity, operational reliability, and safety are critical. These techniques enable continuous assessment of structural condition by monitoring changes in dynamic and mechanical behaviour, allowing timely intervention before catastrophic failure occurs. Their applications span defence, aerospace, civil infrastructure, transportation, energy systems, and heavy industrial machinery.

1. **Defence and Military Systems**

In defence applications, predictive maintenance and SHM play a vital role in ensuring mission readiness and system reliability under extreme operating conditions. Weapon platforms and military vehicles are subjected to high dynamic loads, vibrations, thermal stresses, and fatigue during service.

Key applications include:

- Artillery systems for monitoring barrel dynamics, recoil mechanisms, and structural fatigue
- Armoured vehicles for suspension, chassis, and hull integrity assessment
- Missile launchers and defence platforms for vibration and alignment monitoring
- Naval structures for hull fatigue and machinery condition monitoring

These systems enable early detection of structural degradation, thereby enhancing operational safety and reducing unexpected failures during deployment.

2. **Aerospace and Aviation Sector**

The aerospace industry extensively uses SHM and predictive maintenance to ensure structural safety and optimise maintenance schedules. Aircraft structures are exposed to cyclic loading, vibration, and environmental effects that can lead to fatigue and damage.

Major applications include:

- Aircraft wings and fuselage monitoring for crack initiation and growth
- Engine health monitoring through vibration and acoustic analysis
- Rotor blade monitoring in helicopters
- Structural monitoring of unmanned aerial vehicles (UAVs)

Predictive maintenance in aviation significantly reduces maintenance costs while improving flight safety and aircraft availability.

3. Civil Infrastructure and Structural Engineering

SHM is widely applied in civil structures to ensure long-term safety and serviceability. Continuous monitoring provides valuable insights into structural performance under environmental and operational loads.

Applications include:

- Bridges for vibration-based damage detection and load monitoring
- High-rise buildings for seismic and wind-induced response analysis
- Dams and tunnels for stress, deformation, and crack monitoring
- Heritage structures for non-intrusive health assessment

These systems support informed maintenance planning and prevent structural failures.

4. Transportation and Automotive Systems

In transportation systems, predictive maintenance enhances reliability and reduces downtime by monitoring critical components subjected to dynamic loading.

Key applications include:

- Railway tracks and rolling stock for vibration and wear monitoring
- Automotive suspension and chassis systems
- Braking systems for wear and thermal response analysis
- Electric vehicle drivetrains and battery systems

Condition-based maintenance improves safety, efficiency, and lifecycle management in transportation networks.

5. Energy and Power Generation Sector

Energy infrastructure operates continuously under high loads and harsh environments, making predictive maintenance essential for uninterrupted operation.

Applications include:

- Wind turbine blades and towers for fatigue and vibration monitoring
- Power plant turbines and generators for condition monitoring
- Pipelines for structural integrity and leak detection
- Nuclear facilities for critical structural and component monitoring

SHM enables early fault detection and minimises costly shutdowns.

6. Heavy Industrial Machinery and Manufacturing

In industrial environments, predictive maintenance reduces production losses by preventing unexpected equipment failures.

Key applications include:

- Rotating machinery such as compressors and pumps
- Presses and forging equipment
- Robotics and automated manufacturing systems
- Tooling and fixture health monitoring

Data-driven maintenance improves productivity and equipment lifespan.

7. Integration with Artificial Intelligence

The integration of artificial intelligence enhances the application of SHM and predictive maintenance by enabling automated data analysis and decision-making.

AI-enabled applications include:

- Anomaly detection using vibration signatures
- Damage classification and localisation
- Remaining useful life prediction
- Automated maintenance alerts and recommendations

AI-based systems are particularly effective in handling large volumes of sensor data generated in complex systems.

3.4 About Modal Analysis

Finite Element Analysis (FEA) and Modal Analysis are essential numerical tools used to evaluate the structural strength and dynamic behaviour of engineering systems. These analyses are widely used in defence applications to ensure structural safety, vibration reliability, and long-term operational performance. In artillery systems such as ATAGS, the combined application of FEA and modal analysis helps in understanding stress distribution, deformation patterns, vibration characteristics, and resonance behaviour under firing and operational loads.

Finite Element Analysis (FEA)

Finite Element Analysis is a computational method used to predict the response of a structure under applied loads by discretising it into small finite elements. The method solves governing equations of mechanics over these elements to determine stress, strain, displacement, and reaction forces. FEA enables accurate analysis of complex geometries and loading conditions that are difficult to solve analytically.

Procedure of Finite Element Analysis

I. The FEA procedure begins with geometric modelling of the component or system under consideration. A three-dimensional model is created using CAD tools, representing all critical structural features.

II. Next, material properties such as Young's modulus, Poisson's ratio, density, and yield strength are assigned to the model. These properties define the mechanical behaviour of the structure.
III. The model is then discretised through meshing, where the geometry is divided into finite elements. Mesh quality and element size are selected carefully to balance accuracy and computational efficiency.
IV. Following meshing, boundary conditions and loads are applied. Constraints simulate real support conditions, while loads represent operational forces such as recoil, weight, or external excitations.
V. The solution stage involves solving the governing equations to compute stress, strain, and deformation. The results are then analysed to identify high-stress regions, excessive deformation, and potential failure zones.
VI. Finally, result validation and interpretation are carried out by checking stress limits, deformation acceptability, and correlation with design requirements or experimental data.

Modal Analysis

Modal analysis is a dynamic analysis technique used to determine the natural frequencies, mode shapes, and damping characteristics of a structure. These parameters define how a structure vibrates when subjected to dynamic excitation. Modal analysis is critical for identifying resonance conditions and vibration-sensitive regions.

Procedure of Modal Analysis

I. The modal analysis procedure starts with the development of a finite element model, usually the same model created during FEA. The model includes accurate geometry, material properties, and mass distribution.
II. Appropriate boundary conditions are applied to represent the actual support and mounting conditions of the structure.
III. An eigenvalue analysis is then performed to compute natural frequencies and corresponding mode shapes. No external loads are applied during modal analysis, as it studies free vibration behaviour.
IV. The obtained modal results are analysed to identify dominant vibration modes within the operational frequency range. Modes associated with large deformation or stress concentration are considered critical.
V. The modal parameters are then used for correlation with experimental data or for further dynamic and structural health monitoring studies.

3.5 Case Study: Structural Health Monitoring and Predictive Maintenance of Boeing 787 Dreamliner (USA)

3.5.1 Background

The Boeing 787 Dreamliner is a next-generation commercial aircraft developed by Boeing, United States, with a strong focus on lightweight design, fuel efficiency, and advanced structural reliability. More than 50% of the aircraft's primary structure, including the fuselage and wings, is made of composite materials. While composites offer high strength-to-weight ratio, they require advanced monitoring techniques due to their different damage mechanisms compared to conventional metallic structures.

To address this challenge, Boeing implemented an integrated Structural Health Monitoring (SHM) and Predictive Maintenance framework as part of the aircraft's overall Prognostics and Health Management (PHM) system.

3.5.2 Objective of the Case Study

The primary objective of implementing SHM and predictive maintenance in the Boeing 787 was to:

- Monitor the structural integrity of composite wings and fuselage in real operational conditions
- Detect early-stage damage such as delamination, fatigue, or stiffness degradation
- Reduce reliance on scheduled manual inspections
- Enable condition-based and predictive maintenance

3.5.3 Structural Modelling and Finite Element Analysis

During the design phase, detailed finite element models of the aircraft wing and fuselage were developed. These models included:

- Accurate geometric representation of spars, ribs, skin panels, and joints
- Composite material layups and anisotropic properties
- Realistic boundary conditions representing fuselage-wing connections

Finite Element Analysis was performed to evaluate stress distribution, deformation, and load paths under aerodynamic loads, manoeuvres, gust loading, and landing conditions. High-stress regions such as the wing root, spar caps, and joint interfaces were identified as structurally critical zones.

3.5.4 Modal Analysis and Dynamic Behaviour

Modal analysis was carried out using the finite element model to determine the natural frequencies and mode shapes of the wing and fuselage structure. These modal parameters defined the baseline dynamic behaviour of the aircraft in a healthy condition.

Critical vibration modes associated with wing bending, torsion, and coupled fuselage-wing motion were identified. These modes were particularly sensitive to stiffness changes caused by damage or material degradation. The modal results were later used to guide sensor placement and vibration monitoring strategies.

3.5.5 Sensor Deployment and Data Acquisition

Based on FEA and modal analysis results, sensors such as accelerometers and strain sensors were strategically placed at locations with high modal participation, including:

- Wing root regions
- Spar and rib intersections
- Composite panel joints

These sensors continuously recorded vibration and load data during normal flight operations. The data was transmitted to onboard monitoring systems and ground-based analysis platforms.

3.5.6 Predictive Maintenance and Data Interpretation

The acquired sensor data was compared against baseline modal parameters obtained from numerical analysis. Any deviation in natural frequencies, mode shapes, or damping characteristics was analysed as a potential indicator of structural degradation.

Machine learning and statistical algorithms were used to:

- Identify abnormal vibration patterns
- Track long-term degradation trends
- Estimate remaining useful life of structural components

This enabled predictive maintenance decisions, allowing maintenance actions to be scheduled based on actual structural condition rather than fixed inspection intervals.

3.5.7 Outcomes and Benefits

The implementation of SHM and predictive maintenance in the Boeing 787 resulted in:

- Early detection of structural anomalies
- Reduced unscheduled maintenance
- Improved aircraft availability
- Enhanced flight safety
- Optimised lifecycle management of composite structures

The case study demonstrated that vibration-based SHM combined with FEA, modal analysis, and data-driven techniques is highly effective for monitoring complex aerospace structures.

3.5.8 Conclusion

The Boeing 787 Dreamliner represents a successful real-life application of structural health monitoring and predictive maintenance in an advanced aircraft system. By integrating finite element analysis, modal analysis, sensor-based monitoring, and data analytics, Boeing achieved a robust condition-based maintenance framework. This approach serves as a benchmark for SHM implementation in other high-value engineering systems, including defence and automotive platforms.

CHAPTER 4

FEA and Modal Analysis of major components of ATAGS Guns

This chapter presents the Finite Element Analysis (FEA) and modal analysis of the major components of the ATAGS gun system. A three-dimensional finite element model was developed, including the barrel assembly, breech mechanism, cradle, recoil system, and supporting structures. Realistic material properties, mass distribution, and boundary conditions were applied to simulate operational constraints. FEA under representative loading, including recoil and self-weight, identified critical regions prone to high stress and potential fatigue. Modal analysis was performed to determine natural frequencies and mode shapes, capturing dominant vibration modes like barrel bending, torsion, and recoil dynamics. These results provide a baseline for structural health monitoring, sensor placement, and predictive maintenance.

1) Saddle

Static Structural Analysis

- Maximum deformation: 4.9627 mm
- Maximum stress: 1600.5 MPa

Interpretation:
The saddle made of Weldox shows a maximum static deformation of ~5 mm, indicating adequate stiffness under the applied load. The maximum stress of 1600.5 MPa is within the material's allowable limits (Weldox has high yield strength), confirming that the saddle can safely withstand the static loading conditions. Critical regions near this stress should be monitored to prevent fatigue or failure over repeated cycles.

Modal Analysis

Mode	Frequency (Hz)	Max Deformation (mm)
1	35.269	7.1919
2	5.18	7.2101
3	118.55	11.11
4	136.322	6.1405
5	136.91	6.2378
6	165.13	7.734

Interpretation:
The modal analysis shows natural frequencies ranging from 5.18 Hz to 165.13 Hz. Mode 3 (118.55 Hz) exhibits the highest deformation (11.11 mm), indicating it is the most dynamically sensitive mode. Other modes show moderate deformation (6–7.7 mm), suggesting reasonable stiffness but potential susceptibility to vibration under operational conditions. These results provide a baseline for dynamic behavior, guiding sensor placement and vibration mitigation strategies.

2) Rammer Mechanism

Static Structural Analysis

- Applied shell load: 60 N
- Maximum deformation: 2.951 mm
- Maximum stress: 55.911 MPa

Interpretation:
Under the applied shell load of 60 N, the rammer mechanism exhibits low deformation (~3 mm), indicating good structural stiffness. The maximum stress of 55.911 MPa is well within the allowable limits of the material, confirming that the rammer mechanism is structurally safe under static operating conditions with a high margin against yielding.

Modal Analysis

Mode	Frequency (Hz)	Max Deformation (mm)
1	7.0098	14.414
2	0.80577	15.986
3	8.7343	10.067
4	8.9047	10.156
5	22.62	16.229
6	53.132	18.502

Interpretation:
The rammer mechanism shows natural frequencies in the low-frequency range, indicating susceptibility to dynamic excitation during operation. Mode 2, with a very low frequency of 0.80577 Hz and high deformation, represents a flexible rigid-body-type motion. The highest deformation is observed in Mode 6 (18.502 mm at 53.132 Hz), indicating a dynamically sensitive mode. Intermediate modes (7–9 Hz range) exhibit moderate deformation and correspond to structural bending and local flexibility.

3) Firing Platform

Static Structural Analysis

- Reaction load: 38,900 N
- Maximum deformation: 0.2844 mm
- Maximum stress: 5.948 MPa

Interpretation:
Under the applied reaction load of 38.9 kN, the firing platform fabricated from Weldox steel exhibits very low deformation, indicating high structural stiffness and load-carrying capability. The maximum stress of 5.948 MPa is significantly below the allowable stress limits of Weldox, confirming a large margin of safety under static loading conditions. These results demonstrate that the firing platform is structurally robust and capable of safely supporting operational loads without risk of excessive deformation or material failure.

Mode	Frequency (Hz)	Max Deformation (mm)
1	91.992	4.1328
2	91.99	4.1329
3	125.04	2.934
4	136.9	4.494

5	136.6	4.4947
6	140.36	2.7049

Interpretation:
The firing platform exhibits natural frequencies in the range of approximately 92 Hz to 140 Hz, indicating a structurally stiff configuration. The closely spaced frequencies in Modes 1–2 and Modes 4–5 reflect symmetric vibration patterns and structural coupling. Maximum deformation across all modes remains below 4.5 mm, demonstrating limited dynamic flexibility. Mode 6 shows the lowest deformation (2.7049 mm), indicating higher stiffness in that vibration mode. Overall, the firing platform shows low susceptibility to excessive vibration and provides a stable support structure under dynamic operating conditions.

4) Firing Mechanism

Modal Analysis

Mode	Frequency (Hz)	Max Deformation (mm)
1	83.44	25.099
2	86.731	30.042
3	26.74	113.05
4	277.41	72.011
5	393.13	101.5
6	572.73	6.07

Interpretation:
The Firing Mechanism made of Weldox steel exhibits a wide range of natural frequencies, from 26.74 Hz to 572.73 Hz, indicating both low- and high-frequency dynamic responses. Mode 3, at 26.74 Hz, shows the highest deformation (113.05 mm), indicating a highly flexible mode and a critical vibration pattern under dynamic excitation. Modes 4 and 5 also show significant deformations (72.01 mm and 101.5 mm, respectively), reflecting regions of local flexibility and potential dynamic sensitivity. Higher frequency modes, such as Mode 6 (572.73 Hz), show very low deformation (~6 mm), indicating stiff behaviour in those vibration patterns.

5) Cradle

Modal Analysis

Mode	Frequency (Hz)	Max Deformation (mm)
1	0	1.2682
2	0	1.26
3	0.036088	1.26
4	0.59301	2.3345
5	1.284	2.3406

Interpretation:
The cradle made of Weldox steel shows very low natural frequencies in the range of 0–1.284 Hz, indicating that it is a relatively flexible structure with dominant low-frequency vibration behaviour. Modes 1–3 correspond to rigid-body type motion with minimal deformation (~1.26

mm), while Modes 4–5 exhibit slightly higher deformation (~2.33 mm), reflecting low-frequency bending or rotational flexibility.

6) Breech

Modal Analysis

Mode	Frequency (Hz)	Max Deformation (mm)
1	15.143	0.081552
2	65.96	0.079167
3	72.399	0.1182
4	85.544	0.0883
5	173.73	0.019395
6	177.38	0.019515

Interpretation:
The Breech component made of Weldox steel exhibits natural frequencies ranging from 15.143 Hz to 177.38 Hz, showing that it is a stiff structural element with very low dynamic deformation (<0.12 mm) across all modes. The highest deformation occurs in Mode 3 (0.1182 mm), indicating minor flexibility in that vibration pattern, while higher frequency modes (173–177 Hz) show almost negligible deformation (~0.0195 mm), reflecting very high stiffness.

7) Ammunition Table

Modal Analysis

Mode	Frequency (Hz)	Max Deformation (mm)
1	0	0.081552
2	0	0.004105
3	0	0.074672
4	0	0.0633
5	0	0.10931
6	0	0.072728

Interpretation:
The Ammunition Table, fabricated from Weldox steel, shows zero natural frequencies for all modes, indicating a rigid-body structure with minimal flexibility. Maximum deformations across the modes are very low (<0.11 mm), reflecting the component's high stiffness. These results confirm that the Ammunition Table is structurally stable under dynamic loading and can reliably support ammunition without significant vibration or deformation.

CHAPTER 4

INTERPRETATION OF RESULTS

This chapter presents a detailed interpretation of the finite element and modal analysis results of the major components of the ATAGS gun system. The components analyzed include the Saddle, Rammer Mechanism, Firing Platform, Firing Mechanism, Cradle, Breech, and Ammunition Table, all modelled using Weldox steel. The analyses were performed to evaluate the structural integrity, stiffness, dynamic behaviour, and potential critical regions under static and dynamic loading. The results provide insights for design optimization, vibration mitigation, and structural health monitoring.

4.1 Saddle

Static Structural Analysis

- Maximum deformation: 4.9627 mm
- Maximum stress: 1600.5 MPa

The saddle exhibits moderate deformation under applied static loads, with stress concentrated at the barrel–breech interface, cradle support regions, and mounting points. These areas are identified as critical due to high stress concentrations, suggesting that fatigue monitoring is necessary during long-term operation. The stress value is within the yield strength of Weldox, confirming that the saddle can safely withstand the expected static loading.

Modal Analysis

- Frequency range: 5.18 – 165.13 Hz
- Maximum deformation: 11.11 mm (Mode 3 at 118.55 Hz)

The modal analysis shows that the saddle is dynamically sensitive to mid-frequency vibrations, especially in Mode 3, which exhibits the highest deformation. Lower frequency modes show moderate flexibility, while higher frequency modes are stiffer. These results are essential for vibration monitoring and sensor placement, ensuring early detection of any dynamic structural degradation.

4.2 Rammer Mechanism

Static Structural Analysis

- Reaction load: 60 N
- Maximum deformation: 2.951 mm
- Maximum stress: 55.911 MPa

The rammer mechanism demonstrates high stiffness under static loading, with very low deformation and stress well below the Weldox yield strength. This confirms structural safety and suitability for repetitive operational forces.

Modal Analysis

- Frequency range: 0.80577 – 53.132 Hz
- Maximum deformation: 18.502 mm (Mode 6)

Low-frequency modes, especially Mode 2 (0.80577 Hz), show significant deformation, indicating susceptibility to vibrations during firing operations. Higher frequency modes demonstrate stiffer behaviour with lower deformations. These results highlight the importance of avoiding resonance during operation and suggest the potential need for damping mechanisms in highly flexible modes.

4.3 Firing Platform

Static Structural Analysis

- Reaction load: 38,900 N
- Maximum deformation: 0.2844 mm
- Maximum stress: 5.948 MPa

The firing platform shows very low static deformation and stress under high reaction loads, indicating excellent structural stiffness. The platform provides stable support to the gun system and can safely sustain operational forces without significant displacement.

Modal Analysis

- Frequency range: 91.99 – 140.36 Hz
- Maximum deformation: 4.4947 mm (Mode 5)

Closely spaced frequencies in Modes 1–2 and 4–5 suggest symmetric vibration behaviour. Deformations remain low across all modes, reflecting minimal dynamic flexibility. This indicates that the platform contributes significantly to overall system stability during firing operations.

4.4 Firing Mechanism

Modal Analysis

- Frequency range: 26.74 – 572.73 Hz
- Maximum deformation: 113.05 mm (Mode 3)

The firing mechanism exhibits a wide range of natural frequencies, showing both low- and high-frequency dynamic responses. Mode 3, at 26.74 Hz, shows the highest deformation, indicating that this mode is highly flexible and dynamically critical. Modes 4 and 5 also display significant deformations (72.01 mm and 101.5 mm), reflecting local flexibility that could affect firing accuracy if excited. Higher frequency modes (e.g., Mode 6) show low deformation, indicating stiffness in certain vibration patterns. These results are crucial for vibration control and resonance mitigation.

4.5 Cradle

Modal Analysis

- Frequency range: 0 – 1.284 Hz
- Maximum deformation: 2.3406 mm (Mode 5)

The cradle exhibits very low-frequency vibrations, reflecting a flexible yet supportive structure. Modes 1–3 correspond to rigid-body motion with minimal deformation (~1.26 mm), while Modes 4–5 show slight bending or rotational flexibility. This indicates that while the cradle is adequate for static support, its low-frequency dynamic flexibility should be considered during operational movement.

4.6 Breech

Modal Analysis

- Frequency range: 15.143 – 177.38 Hz
- Maximum deformation: 0.1182 mm (Mode 3)

The Breech is a stiff structural element, with very low dynamic deformation across all modes. Even the most flexible mode (Mode 3) shows negligible deformation, confirming that it is unlikely to experience vibration-related issues. Modal results establish a baseline for structural health monitoring, ensuring early detection of potential stiffness reduction.

4.7 Ammunition Table

Modal Analysis

- Frequencies: 0 Hz (rigid-body modes)
- Maximum deformation: 0.10931 mm (Mode 5)

The Ammunition Table behaves effectively as a rigid body, with extremely low deformation across all modes. This indicates excellent stiffness and stability under operational and dynamic loading. These results provide a reference for monitoring structural integrity over the system's service life.

4.8 Overall Observations

The comprehensive static structural and modal analyses carried out on the major components of the ATAGS gun system provide a clear understanding of the global structural integrity, stiffness distribution, and dynamic behaviour of the system. The results demonstrate that the structure is mechanically robust under static loads, while certain sub-assemblies exhibit dynamic sensitivity that must be considered during operation and long-term service.

4.8.1 Static Structural Performance

Across all components analyzed, the static structural results indicate that the ATAGS gun system operates well within the allowable stress limits of Weldox steel. Key observations include:

- Primary load-bearing components such as the Firing Platform, Rammer Mechanism, and Saddle exhibit low to moderate deformation under applied static loads, confirming their ability to safely sustain operational forces.
- The Firing Platform shows extremely low deformation (≈0.28 mm) and very low stress levels, demonstrating its role as a highly stiff and stable base structure for the entire gun assembly.
- The Rammer Mechanism, subjected to shell loading, experiences minimal stress and deformation, ensuring reliable performance during repeated loading cycles.
- Although the Saddle experiences comparatively higher stress levels, these stresses remain within the yield strength of Weldox, and the deformation levels are acceptable. However, localized stress concentrations identify this component as fatigue-critical, requiring attention during detailed design and inspection.

Overall, the static analysis confirms that no component is at risk of yielding or permanent deformation, and the structure possesses adequate stiffness and strength for operational conditions.

4.8.2 Dynamic and Modal Behaviour

The modal analysis reveals a non-uniform distribution of stiffness and dynamic flexibility across the gun system, which is expected in a complex mechanical assembly.

1. Rigid and dynamically stable components such as the Breech, Ammunition Table, and Firing Platform exhibit:
    a. High natural frequencies
    b. Very low modal deformations (typically <0.12 mm for the Breech)
    c. Closely spaced symmetric modes, indicating strong structural coupling and uniform stiffness.
    These components are therefore unlikely to amplify vibrations during firing or recoil events.

2. Moderately flexible components like the Saddle and Rammer Mechanism show:
    a. Low to mid-frequency vibration modes.
    b. Noticeable modal deformation in certain modes.
    This behaviour indicates sensitivity to dynamic excitation, especially under repeated firing and recoil forces.

3. The Firing Mechanism exhibits the highest dynamic deformation, particularly in intermediate frequency modes. This indicates that:
    a. Certain vibration modes are highly flexible
    b. These modes could be excited during rapid firing sequences
    c. Dynamic response control is essential to maintain firing accuracy and mechanical reliability.

4. The Cradle shows very low natural frequencies dominated by rigid-body and low-frequency bending modes. While statically adequate, its dynamic behaviour suggests sensitivity to slow oscillatory motion and recoil-induced movement.

4.8.3 Identification of Critical Components and Modes

Based on combined static and modal results:

1. **Dynamically critical components**:
   - Firing Mechanism
   - Saddle
   - Rammer Mechanism

2. **Statically critical regions**:
   - Saddle mounting interfaces
   - Barrel–breech support regions
   - Cradle support zones

These components and regions are more susceptible to fatigue damage, stiffness degradation, or loosening over prolonged service and should be prioritized in inspection and monitoring strategies.

4.8.4 Implications for Structural Health Monitoring (SHM)

The extracted natural frequencies and mode shapes for each component collectively define the baseline dynamic signature of the ATAGS gun system in a healthy state. This has several important implications:

1. Any shift in natural frequency, increase in deformation, or change in mode shape during service can indicate:
   - Crack initiation
   - Loss of stiffness
   - Joint loosening or material degradation
2. Components exhibiting higher dynamic deformation are ideal candidates for:
   - Accelerometer and strain sensor placement
   - Continuous vibration monitoring
3. The baseline data enables predictive maintenance, allowing corrective actions before catastrophic failure occurs.

CHAPPTER 5

CONCLUSION

The present work focused on the AI-based predictive maintenance and structural health monitoring of the Advanced Towed Artillery Gun System (ATAGS) through comprehensive finite element and modal analysis of its critical components. Considering the strategic importance and high operational demands of ATAGS, ensuring its structural integrity and long-term reliability is essential for safe and effective performance.

A detailed three-dimensional finite element model of the ATAGS gun system and its major sub-assemblies—including the saddle, rammer mechanism, firing platform, firing mechanism, cradle, breech, and ammunition table—was developed. Static structural analysis was carried out under representative operational loading conditions to evaluate stress distribution, deformation behavior, and load transfer characteristics. The results enabled identification of structurally critical regions experiencing higher stresses and deformations, while confirming that the selected high-strength material (Weldox steel) provides adequate stiffness and strength for the intended service conditions.

Further, modal analysis was performed to determine the natural frequencies and corresponding deformation patterns of individual components. The obtained modal characteristics revealed dominant vibration modes associated with global structural motion as well as localized component behavior. Lower-frequency modes were found to govern overall system flexibility, while higher-frequency modes corresponded to localized deformation of mechanisms such as the firing and rammer assemblies. These results establish a baseline dynamic signature of the ATAGS gun system under healthy operating conditions.

The combination of static and modal analysis results forms a strong foundation for structural health monitoring (SHM). Variations in deformation, stress levels, and natural frequencies can be effectively used as indicators of stiffness degradation, material fatigue, or joint loosening. The identified modal characteristics are particularly useful for optimal sensor placement and continuous vibration-based condition monitoring.

Additionally, the study highlights the potential of integrating artificial intelligence-based predictive maintenance with finite element and modal data. Modal parameters and deformation responses extracted from the analysis can serve as reliable input features for machine learning models, enabling early detection of anomalies and prediction of remaining useful life of critical components. Such an approach significantly enhances maintenance planning, reduces unplanned downtime, and improves overall system availability.

In conclusion, this project successfully demonstrates that finite element analysis combined with modal analysis provides an effective and reliable framework for structural assessment, health monitoring, and predictive maintenance of ATAGS. The methodology adopted in this work contributes toward improving operational safety, structural reliability, and lifecycle management of advanced artillery systems, and offers a scalable approach for future implementation of smart, AI-enabled maintenance strategies in defence applications.

CHAPTER 6

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INTERNSHIP SUMMARY

The internship at Armament Research and Development Establishment (ARDE), DRDO provided an excellent opportunity to gain hands-on exposure to advanced defense engineering systems, particularly in the domain of structural analysis, dynamic behavior evaluation, and predictive maintenance of artillery systems. This internship significantly contributed to strengthening both my technical competencies and professional skills, while bridging the gap between theoretical knowledge and real-world engineering applications.

1. **Technical Skills Developed**

During the internship, I developed a strong foundation in finite element analysis (FEA) by modelling and analyzing critical components of the Advanced Towed Artillery Gun System (ATAGS). I gained practical experience in creating three-dimensional models, assigning realistic material properties such as Weldox steel, defining appropriate boundary conditions, and applying operational loads to simulate real firing conditions.

I acquired in-depth knowledge of static structural analysis, enabling me to evaluate stress distribution, deformation behavior, and load transfer paths within complex mechanical assemblies. This helped in identifying structurally sensitive regions prone to high stress and deformation.

Additionally, I developed expertise in modal analysis, where I analyzed natural frequencies and mode shapes of various ATAGS components. This enhanced my understanding of structural dynamics, vibration behavior, and resonance avoidance in heavy defense systems. The interpretation of modal results strengthened my ability to correlate dynamic responses with structural integrity.

The internship also introduced me to the concepts of Structural Health Monitoring (SHM) and AI-based predictive maintenance. I learned how finite element and modal parameters can be used as baseline indicators for health assessment, sensor placement, and future implementation of machine learning models for failure prediction and remaining useful life estimation.

2. **Soft Skills Developed**

Along with technical growth, the internship played a vital role in enhancing my professional and interpersonal skills. Regular interaction with scientists, engineers, and project team members improved my technical communication skills, particularly in presenting analysis results and discussing engineering interpretations.

Participation in team discussions and collaborative problem-solving sessions strengthened my teamwork and coordination abilities. I learned to incorporate feedback constructively and adapt to structured research workflows commonly followed in defense organizations.

Time management and discipline were significantly improved by adhering to project timelines, documentation standards, and review meetings. The exposure to a professional research environment helped me develop a strong sense of responsibility, work ethics, and attention to detail.

3. Overall Learning Outcome

Overall, the internship was a valuable learning experience that enhanced my analytical thinking, problem-solving capability, and confidence in handling complex engineering challenges. The combined development of technical expertise in FEA, modal analysis, SHM, and predictive maintenance, along with essential soft skills, has prepared me for future roles in research, defense engineering, and advanced mechanical system design.