INTERNATIONAL RESEARCH IN THE FIELD OF AEROSPACE ENGINEERING

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ASSOC. PROF. DR. HAŞİM KAFALI

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EĞİTİM YAYINEVİ GRUBU

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PREFACE

The field of aerospace engineering stands at the forefront of technological innovation, constantly pushing the boundaries of what is possible in design, manufacturing, and operational safety. However, the advancement of this sector relies not only on cutting-edge hardware and materials but also on the competence, training, and environmental conditions of the personnel who maintain these complex systems. This book, titled "International Research in the Field of Aerospace Engineering," aims to bridge the gap between advanced engineering applications and the critical human factors that sustain them. This volume compiles four distinct yet interconnected studies that reflect the multidisciplinary nature of modern aviation research. It moves from the conceptualization of next-generation vehicles to the structural integrity of platforms, and finally, to the educational and environmental dynamics of aircraft maintenance.

The first chapter, *"Conceptual Design and Production of an Amphibious Unmanned Aerial Vehicle Using 3D Printing Technology,"* explores the intersection of additive manufacturing and unmanned systems. It highlights how rapid prototyping and novel material applications are revolutionizing the design process of versatile aerial vehicles capable of operating in diverse environments. The second chapter, *"Structural Health Monitoring in Aerospace Structures: Current Inspection Methods, Technologies, and Future Trends,"* provides a comprehensive analysis of safety assurance. As aerospace structures become more complex, the transition from traditional scheduled maintenance to predictive, condition-based monitoring becomes imperative for operational reliability and longevity. The third chapter, *"The Impact of Aircraft Maintenance Personnel's Training Levels on Maintenance Performance"* shifts the focus to the human element of aviation safety. It critically examines the correlation between pedagogical standards and operational efficiency, underscoring the necessity of rigorous training protocols. The fourth chapter, *" Determination and Evaluation of Noise Exposure of Workshops in Aircraft Maintenance*

Technician Training Institutions " addresses a frequently overlooked environmental factor. It investigates how acoustic conditions in educational workshops influence the learning outcomes and cognitive performance of future maintenance professionals.

Collectively, these chapters offer a holistic view of the current challenges and opportunities in aerospace engineering. We hope that this book serves as a valuable resource for researchers, engineers, educators, and industry professionals, fostering a deeper understanding of both the machine and the human components that define the future of aviation.

We would like to express our sincere gratitude to all our authors who spared no effort in the realization of this book, and to our publisher, Eğitim Yayınevi, for their unwavering support.

Assoc. Prof Dr. Haşim KAFALI

Aerospace engineering is a broad field that encompasses not only the design of advanced vehicles but also the maintenance processes and safety standards that sustain them. *International Research in the Field of Aerospace Engineering* brings together four distinct studies to offer a multidisciplinary perspective on current developments in the industry.The book begins by exploring the intersection of modern manufacturing and vehicle design, specifically focusing on the conceptual design and production of an amphibious Unmanned Aerial Vehicle (UAV) using 3D printing technology. Following this, the text discusses Structural Health Monitoring (SHM), providing an overview of current inspection methods and potential future trends in ensuring structural integrity.In addition to technical systems, the volume considers the human and operational aspects of aviation. It examines how the training levels of aircraft maintenance personnel influence performance and presents a study on noise exposure within aircraft maintenance technician training workshops.

This book aims to provide valuable insights for researchers and students interested in the diverse facets of aerospace engineering technology and management.

CONCEPTUAL DESIGN AND PRODUCTION OF AN AMPHIBIOUS UNMANNED AERIAL VEHICLE USING 3D PRINTING TECHNOLOGY

Erdem Tunca[**], Haşim Kafalı[***]

1. INTRODUCTION

While seaplanes were once a cornerstone of aviation development and enjoyed heavy commercial and military patronage, their prominence faded rapidly after World War II. The rising performance standards of land-based alternatives effectively marginalized the seaplane market, rendering the technology largely outdated. However, recent advancements in unmanned aerial systems have led to the emergence of new unmanned seaplane models, such as the Sea Scout, Gull, and Flying Fish. Since unmanned seaplanes are capable of autonomous takeoff and landing on water without the directional constraints inherent to narrow runways, they are widely utilized in diverse scenarios, including surveillance and inspection, maritime medical transport, and environmental monitoring. Du et al. (2014), emphasized that unmanned seaplanes may encounter issues such as porpoising while taxiing at high speeds across the water surface due to longitudinal dynamic instability. Furthermore, when operating in open seas, unpredictable waves and weather conditions negatively impact flight operations. Unmanned seaplanes typically navigate at speeds exceeding those of traditional boats, rendering them inherently more sensitive to hydrodynamic instability caused by rough waves. In the case of manned seaplanes, pilots can take immediate corrective actions to prevent instability based on their operational experience (Du et al., 2014). In an attempt to maximize aircraft adaptability and widen mission profiles, significant research has gone into developing vehicles capable of both flight and submersion. Although the idea dates back to 1934, the history of human-piloted development is limited to four key prototypes: the LPL, the

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RFS-1, the Convair, and the DARPA submersible. Developing a piloted aquatic-aerial vehicle involves far greater engineering complexities than creating an unmanned platform. Consequently, no such design has yet been successfully realized for effective operation in both mediums (Du et al., 2014).

Yang et al. (2015) emphasize that this hybrid vehicle integrates distinct capabilities: it offers the stealth associated with Unmanned Underwater Vehicles (UUVs) and the surface agility of Unmanned Surface Vehicles (USVs), while retaining the rapid response and aerial velocity typical of standard UAVs. An aquatic UAV is capable of executing complex maneuvers such as aerial flight, aquatic takeoff, landing and loitering, high-speed surface cruising, and underwater navigation. The fusion of design principles from distinct environments grants aquatic UAVs the unique ability to conduct cross-media transitions and navigate autonomously. Such versatility offers immense utility for both defense and commercial sectors, prompting widespread international efforts to develop fully operational systems. Nevertheless, the drastic contrast in the physical characteristics of air and water presents a formidable engineering barrier to creating a vehicle that complies with the dual requirements of both fluids. According to current research, a fully capable aquatic UAV has not yet been realized (Yang et al., 2015).

As depicted in Figure 1, the United States currently dominates the development of seaplane UAV prototypes, which are designed for dual-domain operations. These platforms are capable of autonomous aquatic takeoff and landing, as well as loitering on the water surface. Consequently, their strategic utility lies primarily in conducting reconnaissance and surveillance (ISR) missions within contested maritime and coastal environments. Five seaplane UAV prototypes have been introduced, three of which entered service following flight testing. The United Kingdom has also achieved notable success in the development of such UAVs, with the Gull Series evolving into a mature seaplane UAV system. Furthermore, Figure 2 depicts certain UAVs alongside the biological species that inspired their design during the development phase. Table 1 presents the takeoff and landing methodologies of typical prototypes found in the literature (Yang et al., 2015).

Based on existing research, the concept of seaplane UAVs was first demonstrated by the NASA Ames Research Center in 2002 via the

Autonomous Cargo Amphibious Transport (ACAT). This was paralleled by the creation of the Neptune by DRS Technologies in 2002, designed specifically as a Maritime UAV (MUAV). Progress continued in 2005 with Vought Aircraft Industries unveiling the armed King Fisher II for DARPA, followed by the production of the Sea Scout by Oregon Iron Works (OIW) in 2006 for maritime surveillance. This aircraft became the first seaplane UAV to achieve successful automated navigation by executing autonomous takeoff and water landing. In 2007, the Flying Fish, a UAV capable of autonomous takeoff and landing at sea, was developed by the University of Michigan with support from DARPA. In 2007 and 2008, Warrior (Aero-Marine) Ltd. in the United Kingdom successfully tested the GULL24 and GULL36 seaplane UAVs, respectively. The GULL24 utilized Warrior's 'gull' seaplane configuration, inspired by the seagull. Because the GULL24 is capable of floating on the water surface for extended periods, it facilitates continuous surveillance and detection missions. Regarding mission performance, the GULL36 can traverse 1111 km in 12 hours with an 8 kg payload or cover 240 km in 2.2 hours carrying a 22 kg sensor load. Developed as an advanced iteration of the GULL24, this platform exhibits a 4-meter wingspan, a maximum takeoff weight of 70 kg, and a top speed of 150 km/h (Yang et al., 2015).

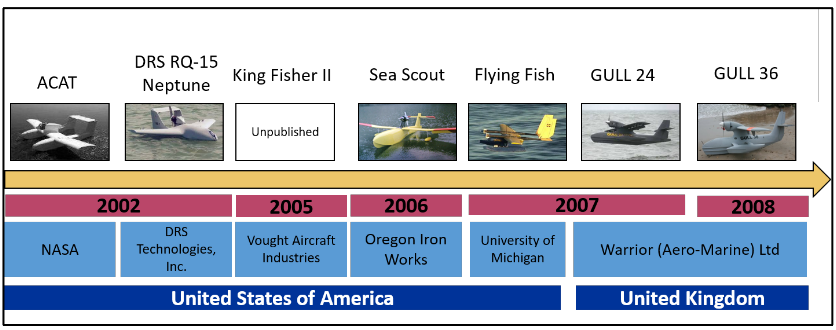


Figure 1. Evolution of seaplane UAVs (Yang et al., 2015)

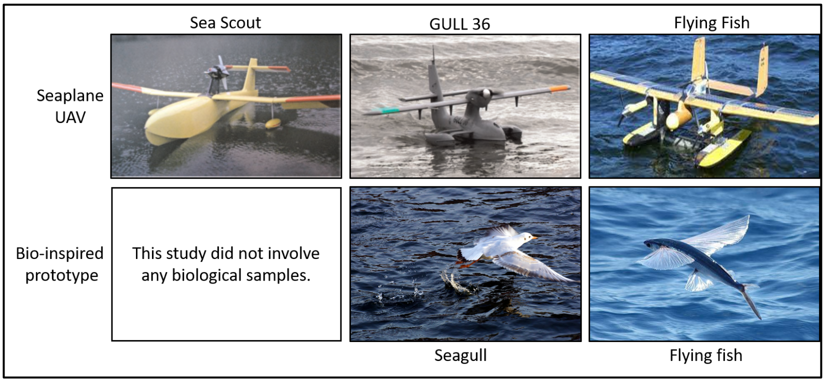
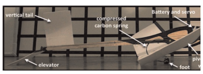
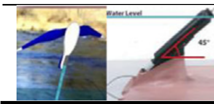


Figure 2. Representative aquatic UAVs with aquatic-aerial potential and their corresponding biological prototypes (Yang et al., 2015)

Table 1. Landing and water takeoff strategies of existing typical aquatic UAVs possessing aquatic-aerial capabilities (adapted from Yang et al., 2015)

Amphibious UAV	Name	Year	Developing Institution	Take-off Method	Landing Method
	GULL Series	2007	Warrior (Aero-Marine) Ltd.	Water taxiing	Glide landing on water surface
	Flying Fish	2007	University of Michigan	Water taxiing	Glide landing on water surface
	Cormorant	2005	Lockheed Martin	Launch mechanism	Vertical descent
	Switchblade	2011	AeroVirone nt Inc	Catapult	Dive landing
	Flying Fish Prototype	2009	Beihang University	Water taxiing	Glide landing on water surface
	Flying Fish Model	2011	MIT	Catapult	Unspecified

	Gannet	2012	MIT Lincoln Laboratory	Hand launch	Dive landing
	Bionic Gannet Prototype	2013	Beihang University	VTOL (Propeller-driven)	Dive landing
	Flying Fish Glide Prototype	2013	Stanford University	Ground-assisted jump take-off	Water-to-land jump
	Flying Squid Prototype	2014	Imperial College London	Water jet propulsion	Dive landing

During the water take-off phase, amphibious aircraft encounter a complex combination of hydrodynamic loads alongside the conventional forces of aerodynamics, propulsion, and gravity. As kinematic variables such as pitch angle, draft, and velocity evolve rapidly, they significantly alter these acting forces. This dynamic behavior highlights the intricate interdependence between the aircraft's motion and the aerodynamic-hydrodynamic force couple (Wang et al., 2020). Amphibious aircraft possess the capability to take off and land on both land and water without altering the structure of any component, making them suitable for specialized missions over wetlands and open seas. Since land-based aircraft lacking reliable engines and aerial refueling capabilities could not perform long-distance missions over the ocean, seaplanes and amphibious aircraft experienced a golden age starting in the early 1930s. Although seaplanes are no longer the primary backbone of air transport today, amphibious aircraft continue to play a crucial role in specialized fields such as private aviation, firefighting, and search and rescue operations. Prominent large-scale aircraft include the Canadian CL-215/415, the Japanese US-1, and the Russian Be-200; additionally, general aviation aircraft such as the Seawind, LA-250, and Be-103 remain popular due to their wide applicability in various domains.

An amphibious aircraft must possess a specialized hull or floats capable of withstanding water impact loads and ensuring stability during water landings. Furthermore, it requires a spray-suppression configuration for the power system, a corrosion-resistant structure, and sufficient reserve buoyancy to prevent sinking or failure in the event of damage or encounters with extreme weather and waves. All these factors make the design for safety and airworthiness of amphibious aircraft significantly more complex than traditional designs. Wu et al. emphasize the importance and difficulty of meeting airworthiness certification requirements and relevant design standards for ultra-light and very light amphibious aircraft with extremely limited empty weight (Wu et al., 2011). In his study, Optimization of a hybrid composite wing for light amphibious applications was undertaken by Chinvorarat, specifically targeting weight and cost reductions under ASTM F-2245 constraints. The wing structure features a combination of woven carbon and glass fiber layers applied to the spar, ribs, and skin. Compliance testing was conducted on a BII2 airframe wing using a universal rig. Outcomes indicated that the hybrid assembly met all load bearing requirements of the standard, remaining free of failure or deformation (Chinvorarat, 2021).

A review of the existing literature reveals that studies have predominantly focused on the design and production of heavy and large-scale systems. In contrast, this study encompasses the design and production of a smaller-scale Unmanned Aerial Vehicle (UAV). The design phase drew inspiration from the Aeromapper Talon and Flightory Stork models. Following the completion of various optimization processes, the produced UAV was designed with a form capable of landing on and taking off from both land and water, featuring a high glide ratio intended for operation in the Muğla region, which is characterized by extensive forests and wetlands. Thanks to their high gliding capacity, these aircraft can fly at low speeds and achieve maximum efficiency in slope soaring (flights utilizing air currents created by wind striking formations such as hills or roofs). By transferring these characteristics, the aim was to enable the UAV to fly within thermals or perform slope soaring, thereby extending its flight duration significantly beyond standard service times. The fixed-wing structure was designed to allow for easy assembly and disassembly before and after flights, aiming for ease of deployment in challenging conditions. During production, additive manufacturing (3D printing) technology was utilized with the goal of realizing a more efficient and safe aircraft production process.

2. MATERIALS AND METHODS

2.1. Theoretical Study and Analyses

At this stage, a comprehensive theoretical investigation was conducted regarding unmanned aerial vehicles (UAVs) and gliders capable of executing similar missions, utilizing academic studies and databases available in the literature. Furthermore, an analysis was performed to distinguish the significant differences between autonomous or non-autonomous aircraft designed specifically as UAVs and contemporary model gliders used in competitions organized by the Fédération Aéronautique Internationale (FAI). These designs were examined in detail to derive average specification data. Among the reviewed UAVs, the Vanilla VA001 stands out as the most notable example, boasting a flight endurance of five days. Based on the data obtained, the key parameters identified for examination include Aspect Ratio (AR), Wing Loading, Wing Area, Airfoil performance, and, for motorized gliders, propulsion performance.

UAV design parameters will be established by combining the obtained theoretical and practical data. The study aims to reach the most accurate inferences during the data analysis. Fluid analyses will be performed using ANSYS and XFLR software, utilizing the selected airfoil and its geometric properties, to obtain C_L/C_D (lift/drag) graphs and data (Fisher et al., 2012; Li & Liu, 2016).

2.2. Unmanned Aerial Vehicle (UAV) Design

Based on the obtained parameters, it is possible to make inferences regarding UAV performance and efficiency using a large dataset comprising information on weight, structure, and flight mechanics. The derivative of the curve representing the variation of wing area with respect to weight denotes the wing loading, a critical variable in aircraft design. When environmental conditions are taken into account, the curve correlating airspeed (relative velocity) with wing loading indicates the aerodynamic performance of the wing section (airfoil). The derived expressions will serve as inputs for the preliminary design calculations of the proposed Unmanned Aerial Vehicle (UAV) platform.

Since the airfoil geometry has a direct impact on performance, investigations conducted during the design phase prior to fabrication indicated that the utilization of the GOE 693 series airfoil aligns with the objectives of this study. Furthermore, the aspect ratio of the wing is of paramount importance in ensuring optimal performance. Through dimensional analysis, it is possible to determine the dimensions of any physical quantity appearing in a given relationship.

The formula utilized for gliding performance is presented in Equation 1 (Tennekes, 2009):

$$\frac{wv_8}{v_e\sqrt{p_0}\sqrt{p}} = C_D\left(\frac{1}{2}p_0V_e^2\right)s + \frac{I}{\pi eb^2}\frac{w^2}{\frac{1}{2}p_0V_e^2} \qquad \text{(Equation 1)}$$

In accordance with these parameters, the effectiveness of a high aspect ratio in gliding flight has been demonstrated, as a shorter chord length—coupled with a large wing area—reduces induced drag. However, this extensive wing area is significantly larger than the ideal wing area required for thermal circling. By increasing the bank angle and consequently reducing the wing loading, a much more efficient turn can be executed within the thermal. The turn radius within a thermal is given by:

$$R = \frac{W}{s}.\frac{2}{\rho g}.\frac{cos^2\gamma}{\sin(\mu)\,C_l} \qquad \text{(Equation 2)}$$

The GOE 693 airfoil was analyzed using the XFLR5 software, and the obtained data were compared with existing values from the database. The maximum lift-to-drag ratio (C_L/C_D) was achieved at an angle of attack (AoA) of approximately 5 degrees. The relevant data are presented in Figures 3 and 4.

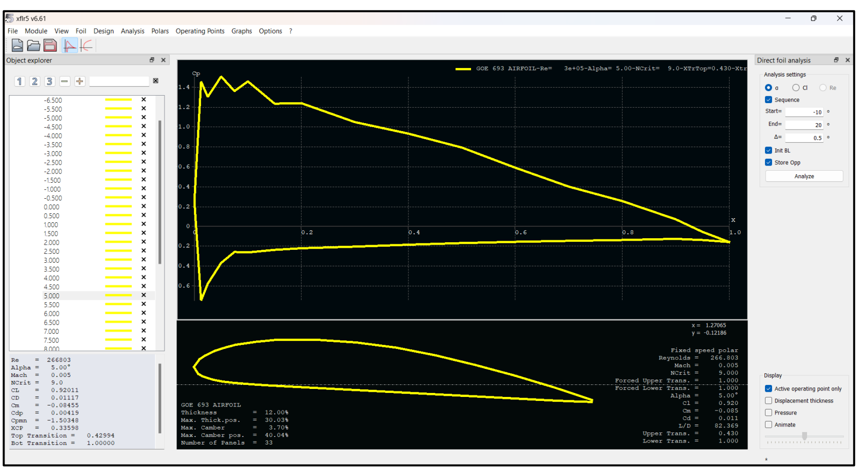


Figure 3. Analysis of the GOE 693 airfoil using XFLR5 software

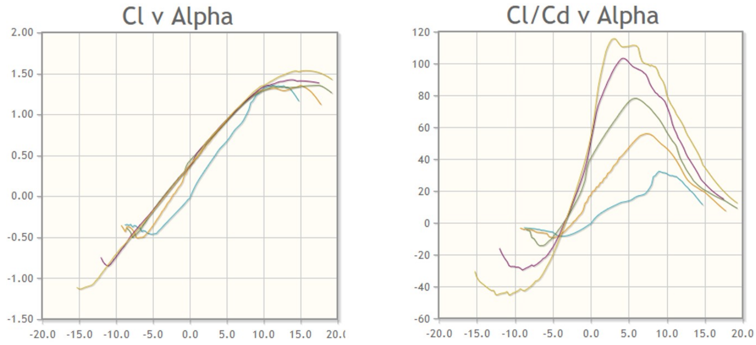


Figure 4. GOE693 airfoil data obtained from databases (GOE 693 AIRFOIL (Goe693-Il), n.d.)

In the wing design process, WingHelper software was utilized in coordination with the CATIA Computer-Aided Design (CAD) software. The aircraft was designed with a wingspan of 1.60 m and a fuselage length of 95 cm. A V-tail configuration was selected over a conventional tail configuration to prevent the tail surfaces from contacting the water. While weight minimization was a primary design criterion, sufficient structural strength was also ensured to withstand the hydrodynamic reaction forces encountered during water landings. Regarding battery selection, preference was given to lighter units capable of providing sufficient power for water takeoff, rather than high-capacity batteries, to avoid the weight penalty associated with larger energy storage systems. Durable and lightweight hollow carbon fiber tubes were utilized as the main spars in the structural design. A visual representation of the designed UAV is provided in Figure 5.

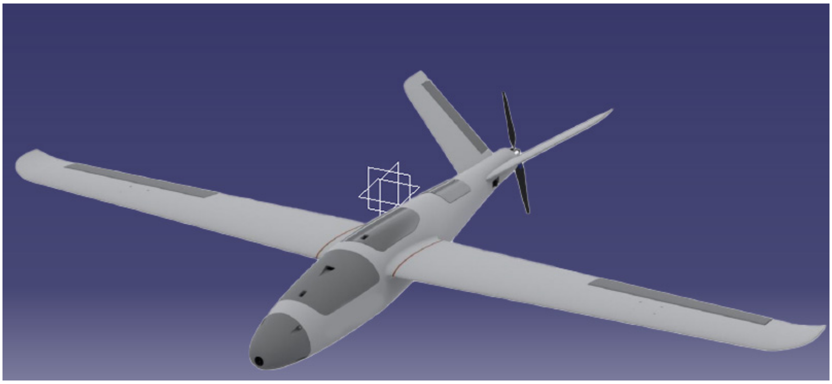


Figure 5. CAD rendering of the designed amphibious UAV

2.3. Unmanned Aerial Vehicle (UAV) Manufacturing

To facilitate the manufacturing process, all components of the UAV were fabricated using Polylactic Acid (PLA) filament via 3D printing technology. A Rigid3D Zero3 model printer with a print bed area of 20x20 cm was utilized for the fabrication. Following the optimization of printing parameters, the fuselage components were printed with a 20% infill density. However, to enhance structural integrity in the regions making initial contact with water, a higher infill density of 25% was employed. Regarding the wing assembly, the wing-fuselage junction—which is subjected to the highest structural loads—was also printed with a 25% infill, while the remaining wing sections were produced with a 20% infill. The entire process, encompassing part optimization and printing, was completed within a period of one month. Post-production, the total weight of the components was measured to be approximately 4 kg. Based on this weight specification, a 380 kV Propdrive motor was selected. Correspondingly, a 22.2 V – 7000 mAh 6S LiPo battery and a 100A Electronic Speed Controller (ESC) were utilized to power the system. The electronic equipment utilized in the system is presented in Figure 6.

Figure 6. Propulsion system components: Battery, ESC, and motor

Figure 7 illustrates the complete set of 3D printed parts for the wing, fuselage, and tail of the UAV.

Figure 7. 3D printed wing, tail, and fuselage components

The 3D printed components were assembled using epoxy resin. Bonding 3D printed UAV components with epoxy resin is a widely adopted technique for ensuring robust and durable connections. This method is particularly suitable for composite or polymer-based 3D prints, as epoxy resin imparts both high mechanical strength and chemical resistance upon curing. To enhance hydrodynamic performance and specifically to facilitate the takeoff phase, a fin-shaped structure was integrated into the ventral section of the fuselage. The fuselage and fin assembly, bonded with epoxy resin, is illustrated in Figure 8. Figure 9 depicts the assembly of the fabricated wing and tail structures with the fuselage. Orange filament was selected for the fabrication of the wings to maximize the visibility of the UAV across air, land, and aquatic environments.

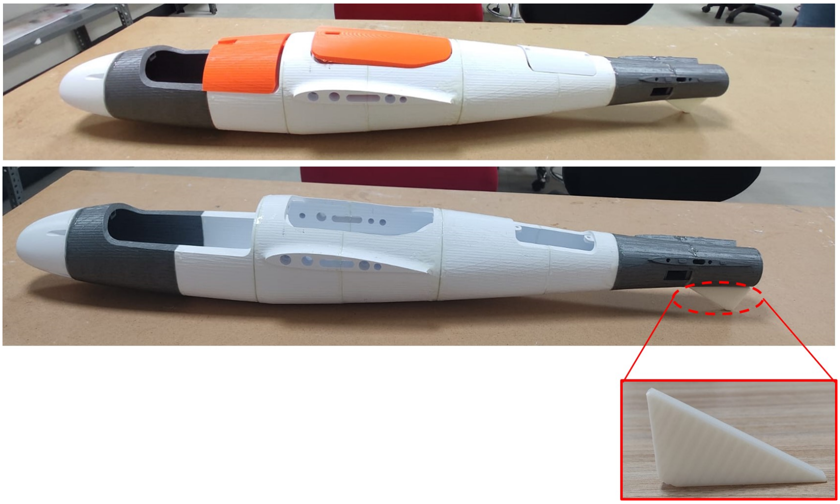


Figure 8. Fuselage and fin structure bonded with epoxy resin

Figure 9. Rear and front views of the manufactured UAV after wing and tail assembly

3. CONCLUSIONS AND RECOMMENDATIONS

In this study, an amphibious radio-controlled UAV capable of performing take-off and landing operations on both land and water was designed and manufactured. The design objectives and technical requirements established at the outset of the study were addressed through an innovative approach and successfully fulfilled. The methodologies, material selection, and manufacturing technologies employed during the design process ensured that the project was executed in accordance with appropriate standards.

In the initial phases of the study, the design parameters and mission profile of the UAV were rigorously defined, and modelling activities were conducted accordingly. The entire workflow, spanning from the design phase to the manufacturing stage, was executed comprehensively. Aerodynamic, hydrodynamic, and structural analyses tailored to the amphibious configuration were performed using various software tools, verifying that the design can operate safely on both land and water.

During the manufacturing process, modern production methods such as 3D printing technology were effectively utilized to achieve a structure that is efficient in terms of both weight optimization and durability. Materials such as epoxy resin, used for the assembly of components, were meticulously selected to ensure both structural integrity and resistance to environmental conditions.

Pre-flight checks of the manufactured prototype have been completed, and basic functional trials on land and water surfaces have been conducted. The results obtained from the design and manufacturing phases demonstrate the UAV's potential to fulfil the intended missions. However, flight tests have not yet been conducted; these are planned to be carried out in the subsequent phase of the study. With the completion of flight tests, the design's performance, stability characteristics, and mission suitability will be validated in greater detail.

In conclusion, this study has successfully met the established design and manufacturing objectives, yielding a significant output from both technical and innovative perspectives. At this stage of the study, the manufactured prototype is flight-ready and holds high potential for success due to its design characteristics. It is anticipated that the results of the flight tests and final evaluations will further reinforce the success achieved in this study and provide guidance for future development efforts.

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STRUCTURAL HEALTH MONITORING IN AEROSPACE STRUCTURES: CURRENT INSPECTION METHODS, TECHNOLOGIES, AND FUTURE TRENDS

Ersin Eroğlu*

1. INTRODUCTION

1.1 Damage and Safety Requirements in Aerospace Structures

Aerospace structures are subjected to variable and strenuous loading conditions throughout their operational lifespans (Boller, 2008; Payne, 1976) Cyclic mechanical loads during flight, thermal cycling, humidity, and corrosive environments can lead to critical defects, particularly in metallic and composite structures. These include fatigue cracks, delamination, fastener failures, and Barely Visible Impact Damage (BVID). (Diamanti & Soutis, 2010a; Qinetiq, 2012) Such damage types pose significant risks to flight safety by directly compromising structural integrity.(Seneviratne & Tomblin, 2010)

Traditional aviation maintenance philosophy relies on periodic inspections performed at specific flight hour intervals or cycle counts (Aviation Rulemaking Advisory Committee (ARAC), 2024; "New Materials for Next-Generation Commercial Transports," 1996). However, the increasing use of composite materials in modern aircraft, coupled with complex geometries and high operational tempos, has highlighted the limitations of conventional maintenance in terms of cost, time, and accessibility. (Muñoz, n.d.) This shift has necessitated the development of more continuous, automated, and real-time monitoring approaches (Cusati et al., 2022; Diamanti & Soutis, 2010b)

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1.2 Evolution from Non-Destructive Testing to Structural Health Monitoring

Non-Destructive Testing (NDT) methods such as ultrasonic testing, radiography, magnetic particle, and eddy current enable defect detection without compromising the structure's utility. While these techniques have been successfully utilized for decades, they are inherently periodic and human-dependent, lacking continuous monitoring capabilities. (Köseoğlu, 2025; Negi et al., 2025)

Structural Health Monitoring (SHM) has emerged as an evolution of the classical NDT approach. SHM systems aim to continuously monitor structural conditions and detect damage at an incipient stage via integrated sensors. This paradigm shifts maintenance strategies from "scheduled maintenance" toward "Condition-Based Maintenance (CBM)" and "Predictive Maintenance" frameworks. (Negi et al., 2025)

1.3 Definition and Scope of Structural Health Monitoring SHM is defined as the integration of sensors, data acquisition, and analysis systems designed to evaluate the current state of a structure, monitor changes over time, and identify damage. (Martins et al., 2020; Scarselli & Nicassio, 2025) In literature, SHM is frequently categorized according to Rytter's four-level damage detection hierarchy (Rytter, 1993; Scarselli & Nicassio, 2025; Scott W. Doebling et al., 1996; Sohn et al., 1996):

- Level 1 (Detection): Is there damage?
- Level 2 (Localization): Where is the damage?
- Level 3 (Assessment): How severe is the damage?
- Level 4 (Prediction): What is the remaining useful life (RUL)?

In aerospace applications, the scope of SHM extends beyond mere damage detection to include load monitoring, residual life estimation, and structural behavior validation (Zhang et al., 2022). Thus, SHM provides a more holistic system approach compared to classical NDT (Ballarin et al., 2025; Romano et al., 2019).

The objective of this book chapter is to provide a comprehensive review and comparative evaluation of current SHM-based inspection methods in aerospace structures. The chapter first introduces the fundamental components of SHM systems, followed by an in-depth analysis of wave-based, vibration-based, and data-driven SHM approaches. Finally, current challenges, certification processes, and future research trends are discussed.

2. FUNDAMENTAL COMPONENTS OF STRUCTURAL HEALTH MONITORING SYSTEMS

Structural Health Monitoring (SHM) systems comprise multiple interacting sub-components designed to assess structural integrity continuously or semi-continuously (Balageas et al., 2010). In aerospace applications, the efficacy of an SHM system depends on the cross-optimization of sensor technologies, excitation/data acquisition infrastructures, and signal processing/decision-making algorithms (Staszewski et al., 2004).

2.1 Sensor Technologies

Sensors represent the most critical layer of SHM, responsible for transducing physical quantities related to structural state. In aviation, sensors must satisfy stringent requirements such as minimal weight penalty, high sensitivity, environmental durability, and long-term stability (Rahul et al., 2018) . The primary characteristics, advantages, and limitations of the most prevalent sensor technologies in aerospace SHM are summarized in Table 1.

Table 1: Comparative Analysis of Primary SHM Sensor Technologies

Technology	Primary Application	Advantages	Key Limitations
PZT	Guided Wave / AE	Active & Passive capability, high, sensitivity	Temperature sensitivity, wiring weight
FBG/DFOS	Strain / Temperature	EMI immunity, embeddable, lightweight	High interrogation system cost
MEMS	Vibration / Modal	Low cost, low power, compact	Low spatial resolution for local damage
Smart Mats.	In-situ Sensing	Weight reduction, "sensor-less" design	Manufacturing complexity, signal noise

2.1.1 Piezoelectric Sensors (PZT)

Piezoelectric (PZT) sensors are among the most prevalent technologies in aerospace SHM. Their dual ability to convert mechanical strain into electrical signals and vice versa allows them to function as both sensors and actuators (Cuc et al., 2007). This reciprocity is particularly advantageous for Guided Wave (GW) based SHM systems (Chen & Makki Alamdari, 2020). While their high-frequency operation enables the detection of micro-scale cracks and delamination, their sensitivity to temperature fluctuations remains a primary constraint, necessitating advanced compensation strategies (Croxford et al., 2007; Giurgiutiu, 2005).

2.1.2 Fiber Optic Sensors (FBG, DFOS)

Fiber optic sensors, particularly Fiber Bragg Gratings (FBG) and Distributed Fiber Optic Sensing (DFOS), are gaining traction due to their immunity to electromagnetic interference (EMI) and multiplexing capabilities (Guemes et al., 2025). These sensors can be embedded within composite laminates during manufacturing, allowing for "birth-to-retirement" monitoring. Although primarily used for strain and temperature mapping, they provide vital data for global state assessment (Pevec & Donlagić, 2019).

2.1.3 MEMS and Accelerometers

Micro-Electro-Mechanical Systems (MEMS)-based accelerometers offer compact, low-power solutions for vibration-based SHM (Mardanshahi et al., 2025). They are instrumental in tracking modal parameters (stiffness, damping) that indicate structural changes. However, their reliance on global structural responses makes them less effective for localizing small, incipient defects compared to ultrasonic methods (Haus et al., 2022).

2.1.4 Smart Materials

Recent advances aim to integrate sensing directly into the material's microstructure. Self-sensing polymer composites, utilizing conductive nanomaterials like carbon nanotubes (CNTs) or graphene, form intrinsic networks that exhibit strain-dependent electrical resistance (piezoresistivity) (Ju et al., 2023; Khan & Umer, 2024; Lemartinel et al., 2022; Lopes et al., 2024; Tao et al., 2025). These materials offer a "sensor-less" approach, potentially reducing weight and complexity.

2.2 Actuation and Data Acquisition

SHM architectures are classified into active and passive systems. Active SHM applies external excitation (e.g., Lamb waves via PZT) to interrogate the structure, offering high sensitivity to defects (Capineri & Bulletti, 2021; Etxaniz et al., 2023). Passive SHM monitors inherent responses, such as acoustic emissions (AE) from crack growth or operational vibrations.

Data acquisition (DAQ) hardware must balance high sampling rates (essential for GW) with aircraft-specific constraints like power consumption and EMI shielding. The shift toward Edge Computing—where initial processing occurs at the sensor node—is a significant trend, reducing telemetry bandwidth requirements (Wong et al., 2022).

2.3 Signal Processing and Feature Extraction

Raw data from SHM sensors is rarely actionable. The data analysis chain typically follows a four-stage workflow (Farrar & Worden, 2012; Worden & Manson, 2007):

1. Pre-processing: Filtering, denoising, and environmental (temperature) compensation.
2. Feature Extraction: Deriving representative metrics (e.g., Root Mean Square (RMS), Wavelet coefficients).
3. Damage Indicator (DI) Formulation: Quantifying deviations from a baseline using statistical measures like Mahalanobis distance.
4. Decision-making: Utilizing thresholds or Machine Learning (ML) to classify damage state.

2.4 Decision Support and Maintenance Integration

The transition from data acquisition to operational action is the most critical phase of the SHM chain. In aerospace applications, SHM is positioned as a "maintenance trigger" that facilitates the shift toward Condition-Based Maintenance (CBM) and Predictive Maintenance (Ballarin et al., 2025; Falcetelli et al., 2022).

A central challenge in this integration is the quantification of system reliability. Traditionally, Probability of Detection (POD) curves are used to evaluate NDT performance. However, for SHM, the industry is shifting toward Model-Assisted Probability of Detection (MAPOD). MAPOD integrates physics-based models with experimental data to account for environmental and operational variability (OEV), significantly reducing the cost of physical testing for system validation (Markus G. R. Sause & Elena Jasiūnienė, 2023).

Furthermore, the integration of Machine Learning (ML) into decision-making layers necessitates alignment with recent regulatory frameworks. The EASA Artificial Intelligence Roadmap 2.0 (2023) provides a structured approach for the "trustworthiness" of AI in aviation, emphasizing:

- Learning Assurance: Ensuring the model generalizes well to unseen flight data.
- Explainability: Understanding the reasoning behind a "damage detected" alert.
- Safety Risk Mitigation: Managing the consequences of False Alarms (PFA) and Missed Detections (PMD)

3. CONTEMPORARY SHM-BASED INSPECTION METHODS IN AEROSPACE APPLICATIONS

Structural Health Monitoring (SHM) methodologies for aerospace structures are categorized based on their underlying physical principles and data acquisition strategies. Given the industry's rigorous safety standards, operational SHM methods must offer high sensitivity to incipient defects while maintaining robustness against environmental and operational variables (OEV).

3.1 Ultrasonic Wave-Based SHM Methods

Ultrasonic wave-based monitoring is one of the most mature and widely researched SHM paradigms. It predominantly utilizes Guided Waves (GW), specifically Lamb waves, which propagate efficiently in thin-walled aerospace components like fuselage skins and wing panels.(Giurgiutiu, 2014)

These systems typically operate in an active framework, where piezoelectric transducers (PZT) act as both exciters and sensors in pitch-catch or pulse-echo configurations. The interaction of these waves with structural anomalies—such as fatigue cracks or delamination induces scattering, mode conversion, and attenuation. However, a significant challenge remains in the dispersion characteristics of Lamb waves and their extreme sensitivity to temperature-induced velocity changes, necessitating advanced signal compensation algorithms (Raghavan & Cesnik, 2007).

3.2 Acoustic Emission-Based Monitoring (AE)

Unlike active ultrasonics, Acoustic Emission (AE) is a passive SHM technique that listens for transient elastic waves generated by the rapid release of energy from localized sources, such as fiber breakage or crack propagation (Bogdanov et al., 2023).

AE is uniquely capable of monitoring damage kinetics in real-time, making it invaluable during structural qualification tests. Nevertheless, its deployment in-flight is hindered by high-background noise (aerodynamic and engine vibrations). Current research focuses on advanced "source discrimination" using deep learning to filter structural damage signals from ambient noise (Grosse et al., 2022).

3.3 Vibration-Based Structural Health Monitoring

Vibration-based SHM assesses global dynamic properties—natural frequencies, mode shapes, and damping ratios. Since damage alters the stiffness matrix ($[K]$) or mass distribution ($[M]$) of a structure, these changes manifest in the modal parameters (Doebling et al., 1998).

While effective for global assessment of large assemblies (e.g., control surfaces), this method often lacks sensitivity to small, localized defects. Consequently, it is frequently integrated into hybrid frameworks where global vibration data triggers more localized ultrasonic inspections (Cawley & Adams, 1979).

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3.4 Thermal and Electrical-Based SHM Approaches

Thermal SHM: Utilizes infrared thermography or embedded sensors to detect anomalies in thermal diffusivity caused by subsurface defects (Maldague, 2001).

Electrical SHM: Particularly relevant for Carbon Fiber Reinforced Polymers (CFRP), this method leverages the intrinsic conductivity of carbon fibers. By measuring changes in electrical resistance or impedance, damage such as delamination can be detected without external sensors (Lee et al., 2021). This "self-sensing" capability is a major focus for next-generation composite aircraft.

3.5 Hybrid and Multi-Sensor SHM Systems

To mitigate the limitations of individual modalities, the aerospace industry is moving toward Hybrid SHM. By employing Data Fusion integrating, for example, AE for crack initiation and Guided Waves for damage sizing the reliability of the diagnosis is significantly enhanced.

These hybrid architectures are essential for the realization of Digital Twins, where real-time sensor data is continuously fed into high-fidelity structural models to predict the Remaining Useful Life (RUL) (Staszewski et al., 2004; Xiang et al., 2018).

4. Comparison of Structural Health Monitoring (SHM) and Conventional Non-Destructive Testing (NDT)

4.1 Role of Conventional NDT Methods in Aerospace Structures

Non-Destructive Testing (NDT) has served as the cornerstone of airworthiness for decades. Techniques such as ultrasonic testing (UT), radiographic testing (RT), and eddy current testing (ECT) provide high-fidelity snapshots of structural integrity. However, conventional NDT is inherently **episodic**. It requires the aircraft to be out of service, often necessitating extensive disassembly to grant sensor access to internal primary structures (Ballarin et al., 2025; Diamanti & Soutis, 2010a; Hassani et al., 2021; Steinweg & Hornung, n.d.). The reliance on human operators also introduces variability in detection performance, particularly under the time pressures of commercial or military turnaround cycles.(Abdollahi-Mamoudan et al., 2025; *Comprehensive Guide to Nondestructive Testing (NDT) Methods*, n.d.; *The Crucial Role of Non-Destructive Testing (NDT) in Aviation*, n.d.)

4.2 Distinctive Characteristics of the SHM Approach

SHM represents a paradigm shift from "inspecting the structure" to "the structure sensing itself." By utilizing permanently installed or embedded sensor networks, SHM facilitates monitoring during actual flight conditions. Unlike NDT, which identifies damage after it has reached a certain threshold between intervals, SHM aims to capture the inception and evolution of defects. This capability is the fundamental enabler for Condition-Based Maintenance (CBM), where maintenance is triggered by the actual state of the component rather than fixed flight hours.(Ferreira et al., 2022)

4.3 Technical Comparison Between SHM and Conventional NDT

The following table provides a technical distillation of the trade-offs between these two approaches. As noted in literature, the primary "cost" of SHM's high temporal resolution is its increased sensitivity to Environmental and Operational Variability (OEV), which conventional NDT avoids by operating in controlled ground environments (Balageas et al., 2010; Guemes et al., 2020).

Table 2: Comparative Analysis of Classical NDT and SHM

Criterion	Conventional NDT	Structural Health Monitoring
Inspection mode	Periodic, manual	Continuous / semi-continuous, automated
Structural integration	Temporary sensors	Permanent sensor network
Damage detection timing	At inspection events	Real-time or near real-time
Human dependency	High	Reduced (data-driven)
Accessibility requirements	High	Low
Early damage detection	Limited	High potential
Sensitivity to environment	Relatively low	High (requires compensation)
Certification maturity	High	Emerging

4.4 Certification and Acceptance Considerations

The path to full SHM integration is governed by regulatory bodies such as the FAA and EASA. Currently, SHM is categorized under three main implementation levels (Giurgiutiu, 2014):

1. Advisory SHM: Systems that provide supplementary data but do not replace scheduled NDT.

2. Scheduled Maintenance Credit: SHM data allows for the extension of conventional inspection intervals.

3. Substitution SHM: SHM completely replaces a specific NDT task (currently limited to hard-to-access, non-critical areas).

A major hurdle for certification is the Probability of Detection (POD). While NDT has decades of statistical data to support its POD curves, SHM must rely on MAPOD (Model-Assisted POD) to prove that embedded sensors will remain reliable over the 20-30 year lifespan of an airframe (Farrar & Worden, 2007; Markus G. R. Sause & Elena Jasiūnienė, 2023).

5. DATA-DRIVEN AND ARTIFICIAL INTELLIGENCE-BASED APPROACHES

The transition from traditional signal processing to Artificial Intelligence (AI) and Machine Learning (ML) in SHM has been accelerated by the proliferation of high-density sensor networks. In aerospace applications, where structures exhibit non-linear behaviors and are subjected to complex loading, data-driven methods provide the necessary tools to extract actionable intelligence from high-dimensional datasets (Keith Worden et al., 2020).

5.1 Principles of Data-Driven SHM

Data-driven SHM operates on the premise that damage manifests as statistical anomalies within the measured structural response. Unlike physics-based models, these approaches rely on Pattern Recognition to identify deviations from a "healthy" baseline (Sohn et al., 1996).

The robust implementation of this workflow in aviation requires addressing Operational and Environmental Variability (OEV). Factors such as temperature-induced stiffness changes or fuel-load variations can easily be misclassified as structural damage, necessitating advanced normalization techniques like Principal Component Analysis (PCA) or Cointegration (Cross et al., 2011; Sohn, 2007).

5.2 Machine Learning Paradigms in Damage Detection

Machine Learning algorithms in SHM are broadly categorized by the availability of "labels" (i.e., known damage states) in the training data:

- Supervised Learning: Utilized when datasets for both "healthy" and "damaged" states are available (e.g., Support Vector Machines, k-NN). While highly accurate in lab settings, the scarcity of real-world "damage labels" from operational aircraft limits their direct deployment (Mitra & Gopalakrishnan, 2016).
- Unsupervised Learning: The primary paradigm for aerospace SHM. By training only on healthy-state data, algorithms like Gaussian Mixture Models (GMM) or Outlier Analysis (using Mahalanobis distance) detect damage as a statistical departure from the norm (Sohn et al., 2001).

5.3 Deep Learning and Feature Learning

Deep Learning (DL) has shifted the focus from manual feature engineering to Automated Feature Learning.

Convolutional Neural Networks (CNNs): Highly effective for processing time-frequency representations (e.g., Spectrograms or Wavelets) of ultrasonic signals (Tang et al., 2022).

Autoencoders: Used for dimensionality reduction and anomaly detection by learning to reconstruct healthy signals; a high "reconstruction error" serves as a robust damage indicator.

5.4 Digital Twins and SHM Integration

The Digital Twin (DT) concept represents the ultimate synthesis of SHM and numerical modeling. In this framework, SHM data acts as the "nervous system," providing real-time updates to a high-fidelity finite element model. This enables Prognostics and Health Management (PHM), allowing operators to predict the Remaining Useful Life (RUL) with high confidence (Glaessgen & Stargel, 2012; Tuegel et al., 2011).

5.5 Challenges and Regulatory Barriers: The Need for Explainable AI (XAI)

Despite their high predictive accuracy, data-driven and deep learning models face significant hurdles in the aerospace sector, primarily due to the "black-box" nature of complex neural networks.

A critical research frontier is the development of Explainable AI (XAI) frameworks. For a system to be certified by authorities like EASA or FAA, it is not sufficient for an algorithm to simply detect damage; the system must provide an interpretable justification for its decision (i.e., *which features of the ultrasonic signal led to the "damage" classification?*). XAI techniques, such as SHAP (SHapley Additive exPlanations) or LIME (Local Interpretable Model-agnostic Explanations), are increasingly being integrated into SHM architectures to bridge the gap between high-dimensional data processing and human-in-the-loop decision-making. This transparency is vital for ensuring "Trustworthy AI" as outlined in the EASA AI Roadmap 2.0 (2023).

6. CERTIFICATION, STANDARDS, AND INDUSTRIAL IMPLEMENTATION

The transition of Structural Health Monitoring (SHM) from a laboratory-proven concept to an industrially certified solution remains the most significant challenge in aerospace engineering. Unlike conventional NDT, which is a snapshot event, SHM is a system-level integration. Therefore, its certification requires validating not only the sensor hardware but also the entire data-to-decision chain, including algorithm robustness and long-term durability under flight-cycle stresses (Diamanti & Soutis, 2010c; Farrar & Worden, 2012).

6.1 Regulatory Perspective and Safety Equivalence

Aviation authorities, such as the FAA and EASA, require that any SHM implementation demonstrate "safety equivalence" to existing scheduled maintenance tasks. The regulatory focus is primarily on managing the risks associated with Operational and Environmental Variability (OEV).

The primary pillars of regulatory acceptance include:

- Reliability Quantification: Detection performance is measured through Probability of Detection (POD). Modern frameworks are shifting toward Model-Assisted POD (MAPOD) to account for the impracticality of conducting thousands of physical "run-to-failure" tests on full-scale airframes (Markus G. R. Sause & Elena Jasiūnienė, 2023).
- False Alarm Mitigation: In a commercial environment, a "False Positive" (Type I error) leads to unnecessary aircraft grounding and substantial economic loss. Authorities demand robust compensation algorithms to ensure that environmental noise (e.g.,

thermal expansion) is not misidentified as damage. (Farrar & Worden, 2012)

6.2 Standards and Guidance Documents

While a single unified global standard is emerging, several documents currently serve as the primary Means of Compliance (MoC) for SHM certification:

- SAE ARP6461A / ARP6462: These are the foundational guidelines for implementing SHM on fixed-wing aircraft, defining the requirements for lifecycle management and system verification (SAE International, 2021).
- ASTM E2862: This standard defines the statistical rigor required for POD analysis using "hit/miss" data, which is essential for autonomous detection algorithms (ASTM, 2018).
- EASA Research Agendas (2025-2027): Recent initiatives emphasize the integration of SHM with Condition-Based Maintenance (CBM) and the use of Digital Twins as a certified method for structural life extension (EASA, 2024).

6.3 Industrial Deployment and Case Studies

Industrial adoption is often driven by "hotspot monitoring"—targeting specific areas where conventional access is difficult or where early damage detection provides a clear ROI (Zhao et al., 2007).

- Commercial Aviation: Airbus and Boeing have explored PZT-based guided wave systems for monitoring fatigue in wing-box fasteners and identifying delamination in composite tail surfaces (Qing et al., 2019).
- Rotorcraft and Military UAS: Due to high dynamic loading, rotorcraft use fiber-optic sensing for real-time load monitoring. Unmanned Aerial Systems (UAS) serve as "early adopters" of SHM due to more flexible regulatory frameworks, allowing for the rapid testing of AI-driven prognostic systems (Ciminello et al., 2023; Hesham Azzam & Jim McFeat, 2016).

6.4 Liability and Risk Management in SHM Deployment

A significant yet often overlooked challenge in the industrialization of SHM is the allocation of legal liability. The transition from human-centric inspections to sensor-based automated detection shifts the burden of responsibility among aircraft manufacturers (OEMs), sensor providers, and software developers.

In the event of a structural failure, a critical legal distinction must be made between hardware malfunction (e.g., sensor debonding or signal loss) and algorithmic failure (e.g., a "False Negative" due to software bias or inadequate training data in an AI model). Unlike traditional NDT, where the certified inspector bears the primary responsibility for the "sign-off," SHM requires a new liability framework that addresses software integrity and "decision-traceability." This legal complexity is one of the primary reasons why regulators currently favor a "human-in-the-loop" approach, where SHM data serves as a decision-support tool rather than an autonomous authority (EASA, 2024; Markus G. R. Sause & Elena Jasiūnienė, 2023).

7. CURRENT CHALLENGES AND RESEARCH GAPS

Despite the transformative potential of Structural Health Monitoring (SHM) in aerospace, its transition from controlled laboratory environments to cross-continental flight operations is hindered by several technical and systemic bottlenecks. This section synthesizes the critical limitations and research gaps identified in contemporary literature (Malekloo et al., 2022; Markus G. R. Sause & Elena Jasiūnienė, 2023; Scarselli & Nicassio, 2025).

7.1 Sensitivity to Operational and Environmental Variability (OEV)

Aerospace structures operate under extreme fluctuations in temperature, humidity, and dynamic loading. These factors induce signal changes that often exceed the magnitude of damage-induced signatures, particularly in guided-wave and vibration-based modalities.

The primary research gap lies in the lack of long-term validation under real flight envelopes. While compensation techniques like *Baseline Signal Stretch (BSS)* or *Cointegration* show promise, their reliability over thousands of flight hours remains a critical area for investigation (Ogunleye et al., 2024; Philibert et al., 2022).

7.2 Sensor Durability and "Self-Diagnostics"

A significant concern for airworthiness is whether the sensor will outlast the airframe. Sensors (PZT, Fiber-optics, MEMS) are susceptible to adhesive degradation, moisture ingress, and thermal fatigue.

- The "Sensor Health" Gap: There is an urgent need for robust self-diagnostic algorithms that can distinguish between a failing sensor and a failing structure. Without this capability, SHM systems risk increasing the maintenance burden through sensor-related false alarms (Ghaderiaram et al., 2025; Langat et al., 2025).

7.3 Advanced Damage Localization and Quantification

While Level 1 SHM (Detection) is reaching maturity, Level 2 (Localization) and Level 3 (Quantification) face significant hurdles in complex, anisotropic composite geometries. Wave scattering at stiffeners, ribs, and fasteners complicates signal interpretation. Future research must focus on integrating local-global hybrid sensing architectures to provide the spatial resolution required for critical repair decisions (Balasubramaniam et al., 2023; Choi et al., 2018).

7.4 Data-Driven Limitations and the "Small Data" Problem

Machine Learning (ML) in SHM is constrained by the scarcity of "run-to-failure" or labeled damage data from operational aircraft.

- Research Trend: To bridge this gap, research is shifting toward Physics-Informed Neural Networks (PINNs) and Transfer Learning, where models trained on high-fidelity simulations (Digital Twins) are adapted to real-world aircraft data with minimal physical labeling (Battu et al., 2025; Soleimani-Babakamali et al., 2023).

7.5 Frameworks for Certification

As noted in Chapter 6, the absence of a standardized, tailored certification framework specifically for autonomous SHM remains a major barrier. Establishing "Safety Equivalence" requires a consensus on reliability metrics that go beyond traditional hit/miss POD analysis (Meissner et al., 2025).

8. FUTURE TRENDS IN AEROSPACE SHM

The trajectory of Structural Health Monitoring (SHM) is shifting from being a specialized inspection tool toward becoming a fully integrated lifecycle management system. This evolution is fueled by the convergence of low-power sensing, advanced analytics, and the digitalization of aviation (Chia et al., 2024; Mardanshahi et al., 2025).

8.1 Wireless and Distributed SHM Architectures

The parasitic weight of cabling remains a primary deterrent for large-scale SHM deployment in commercial aircraft. Wireless Sensor Networks (WSNs) offer a solution by enabling high-density monitoring with minimal structural modification. Current research focuses on overcoming the "Faraday cage" effect of metallic fuselages and ensuring strict electromagnetic compatibility (EMC) and data synchronization in high-vibration environments (Gao et al., 2018; Vujić, 2015).

8.2 Energy Harvesting and Self-Powered Nodes

To achieve true "fit-and-forget" capability, SHM sensors must move away from battery dependence, which adds a secondary maintenance burden. Energy Harvesting (EH) from ambient sources—such as thermal gradients between the cabin and external skin, or piezoelectric harvesting from airframe vibrations—enables autonomous, perpetual monitoring (Walber et al., 2022; Zelenika et al., 2020).

8.3 Digital Twin Integration and PHM

As aircraft enter the era of Digital Engineering, SHM data serves as the continuous feedback loop for Digital Twins. This integration facilitates Prognostics and Health Management (PHM), where real-time structural data is fused with flight history to simulate damage progression. This "virtual-to-physical" synchronization is expected to be a cornerstone for future virtual certification (Dragos & Smarsly, 2025; Xu et al., 2025).

8.4 AI-Driven Autonomous Decision Support

Future SHM platforms will transition from "detecting" damage to "recommending" maintenance actions. AI-enabled systems will manage high-dimensional data to quantify operational risk in real-time. However, the path to autonomy is paved with the need for Explainable AI (XAI) to satisfy the stringent verification requirements of aviation safety boards (Bello et al., 2024; Malekloo et al., 2022)

8.5 SHM for Next-Generation Platforms (UAM and Hydrogen Aviation)

The rise of Urban Air Mobility (UAM), eVTOLs, and hydrogen-powered aircraft introduces new structural challenges, such as cryogenic fuel tank monitoring and high-cycle loading from multiple rotors. For these high-tempo, short-haul operations, SHM is not an option but a necessity to minimize turnaround times and ensure safety in uncrewed or minimally crewed flights (Chia et al., 2024; Scarselli & Nicassio, 2025).

9. CONCLUSIONS

This chapter has provided a comprehensive review of contemporary Structural Health Monitoring (SHM) methodologies within the aerospace sector, synthesizing the transition from traditional periodic inspections to a predictive, state-aware maintenance paradigm. By evaluating the inherent limitations of conventional Non-Destructive Testing (NDT)—specifically regarding downtime, accessibility, and human dependency—SHM has been framed as a critical enabler for enhanced flight safety and operational efficiency.

The synthesis of various modalities leads to several concluding observations:

- Methodological Diversity: Guided ultrasonic waves, acoustic emission, and vibration-based monitoring each possess unique sensitivities. However, the literature increasingly highlights that hybrid and multi-sensor architectures are the most industrially relevant path, as they mitigate the limitations of single-modality solutions when applied to complex, anisotropic aerospace structures.
- The Intelligence Layer: Machine Learning and Deep Learning have revolutionized the extraction of damage indicators from high-dimensional datasets. Nevertheless, the high sensitivity of these models to Operational and Environmental Variability (OEV) remains a primary challenge. The integration of data-driven models with physics-based Digital Twin frameworks is identified

as the most robust strategy for maintaining the interpretability and traceability required in aviation.

- Regulatory Maturity: Certification remains the final frontier for SHM. While current standards position SHM as a supplementary capability, the shift toward Condition-Based Maintenance (CBM) requires a more rigorous definition of "safety equivalence" and standardized Probability of Detection (POD) metrics.
- Future Directions: The next decade of SHM will be defined by autonomy and sustainability. Wireless sensor networks, energy-harvesting nodes, and autonomous decision-support systems will move SHM from a maintenance-assisting tool to a "design-for-maintainability" core element, particularly for next-generation platforms such as UAVs and Urban Air Mobility (UAM) vehicles.

In conclusion, SHM is poised to be the "nervous system" of future aircraft. This chapter serves as a reference framework for academic and industrial stakeholders, supporting the continued development of technologies that bridge the gap between structural integrity and digital intelligence.

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THE IMPACT OF AIRCRAFT MAINTENANCE PERSONNEL'S TRAINING LEVELS ON MAINTENANCE PERFORMANCE

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1. INTRODUCTION

By nature, human beings are entities characterized by inherent limitations and a predisposition toward error. An analysis of aviation accident causality reveals that the proportion of human-induced errors has increased over the years; conversely, accidents attributed to mechanical failure have shown a consistent decline. Consequently, the human factor plays a critical role within the aviation industry. Aircraft maintenance is a service fundamentally dependent on human performance. Regardless of the sophistication of automation, technological advancements, or economic resources, humans remain the most vital components of the system, responsible for executing maintenance and inspections. Furthermore, it is the human element that must design and implement the very systems intended to mitigate error.

Aircraft require maintenance at specific intervals or upon reaching defined flight-hour milestones. In a broad sense, maintenance is a comprehensive term encompassing various tasks across numerous industries and diverse work environments. Within the specialized field of aircraft maintenance, two primary professional roles predominate: the airframe and powerplant (mechanical) technician and the avionics technician. Aircraft maintenance personnel are the individuals responsible for performing scheduled maintenance, repairs, servicing, and inspections in accordance with standards established by regulatory authorities to ensure optimal aircraft performance. For these technicians, education and training represent the primary intervention for enhancing competence and situational awareness, overcoming inherent human limitations, and

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mitigating the occurrence of errors. Technicians possessing higher levels of proficiency and situational awareness are demonstrably less likely to commit errors during maintenance procedures.

2. Human Factors in Aviation

An analysis of the causes of aviation accidents reveals that while human-induced errors have increased over the years, accidents resulting from mechanical failures have conversely decreased. Consequently, the human factor plays a pivotal role in aviation. A comprehensive study on aviation accidents conducted by Wiegmann and Shappell demonstrated that human error is responsible for 70% to 80% of all aviation accidents. It is increasingly recognized that the human element represents the most significant source of risk for safe and efficient aviation. The concept of the human factor can essentially be defined as a multidisciplinary field aimed at optimizing human performance and minimizing human error, as well as an applied science that investigates the relationship between humans and other humans or machines (Wickens et al., 2004). The International Civil Aviation Organization (ICAO) defines 'Human Factors' as a multidisciplinary field devoted to gathering information on human capabilities and limitations and applying this knowledge to ensure that human performance is guided in a safe, efficient, and beneficial manner.

By nature, human beings are entities with limited capabilities and a predisposition toward error. Particularly within the aviation profession, all personnel operating both in the air and on the ground strive to minimize problems stemming from human factors, which arise due to limited individual performance levels. Although the majority of known accidents in the aviation world result from errors caused by a decline in human performance, and while this fact is acknowledged by all stakeholders in the industry, ensuring flight safety and preventing accidents requires moving beyond the 'to err is human' philosophy and instead investigating the root sources of these errors.

The systematic study of human factors in the aviation industry began in the 1960s as a direct consequence of the intensive use of jet-engine aircraft in commercial passenger service. During those years, as aircraft accidents were generally perceived to stem from technical failures, the proportion of human factors in accidents was determined to be 20%. By the 1990s, however, the share of human factors in accidents began to be observed at the 80% level. The reason for this shift is the realization that even when technical inadequacies are resolved through technological innovations—as seen in the May 2020 crash of the Pakistan International Airlines A320 in Karachi—accidents persist, highlighting human error as the core problem. Several widely used systemic models exist for evaluating and analyzing the human factor. Among these are the SHELL model, the Swiss Cheese Model, and the HFACS model.

The SHELL (Software, Hardware, Environment, Liveware, Liveware) model is an approach that characterizes the interaction of the human (Liveware) with software, hardware, environment, and other people during the execution of a task. This model, shown in Figure 1, requires an understanding of the effects of all elements, including the environment, equipment, hardware, and other individuals, that influence the performance of a task.

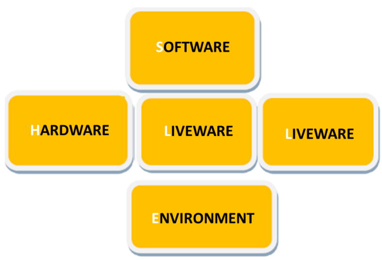


Figure 1. SHELL Model (Basdemir, 2020, 4).

According to the Swiss Cheese Model, accidents occur when human-originated errors across various domains—such as maintenance, cabin operations, weather conditions, terrain, managerial oversight, and air traffic control—align along the same trajectory. In other words, analogous to the structure of Swiss cheese, there are 'holes' or vulnerabilities within the various layers of defense established for the execution of flight operations. Figure 2 shows holes that can be identified as either active human error or hidden systemic failures. Closing these gaps is only achievable by maintaining human performance at an optimal level and reinforcing systemic defenses. Should these vulnerabilities align and overlap, accidents or catastrophic failures within flight operations become inevitable.

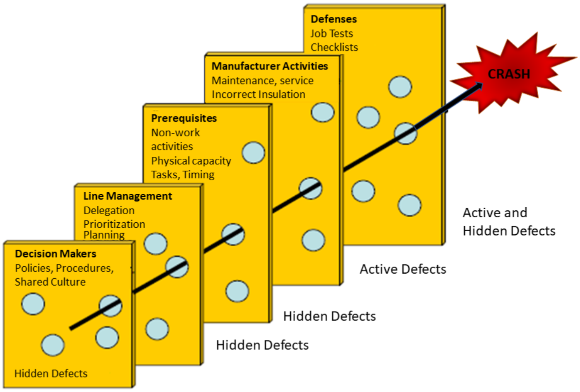


Figure 2. Swiss Cheese Model (Aksoy, 2006).

The Human Factors Analysis and Classification System (HFACS) framework systematically examines accidents and incidents through the lens of human factors within a comprehensive error chain. Figure 3 shows the classification types of the HFACS model. This model investigates the extent to which specific entities or elements at both the organizational and individual levels contribute to the causal sequence within a flight safety culture. Furthermore, it serves as a diagnostic tool to identify the sources of active and hidden sources of failure that emerge during an accident.

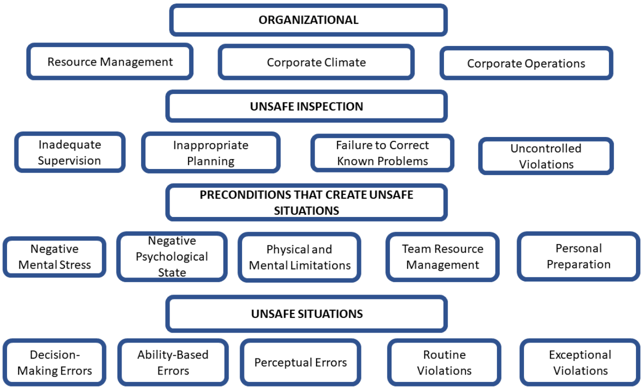


Figure 3. HFACS Model (Basdemir, 2020, 4).

Despite the low statistical risk level in aviation, investigations into aircraft accidents demonstrate that minor errors can precipitate major catastrophes. Factors such as bird strikes, lightning strikes, adverse meteorological conditions, human error, and technical failures may lead to aviation accidents.

According to Reason's Model, all accidents emerge from a combination of both active failures and latent conditions. Failures or violations that manifest their adverse effects immediately are defined as 'active failures.' These errors typically originate from frontline personnel, such as pilots, air traffic controllers, and aircraft maintenance technicians. Examples of active failures include an airport operator failing to conduct braking tests despite heavy snowfall, a balloon pilot pulling the wrong cord and inadvertently opening the parachute vent, or an air traffic controller directing a pilot to the incorrect runway threshold. Conversely, 'latent conditions' are errors whose consequences remain hidden due to an action performed or a decision made long before an accident occurs. Such errors generally stem from regulatory authorities and high-level decision-makers. Since latent conditions are not initially perceived as threats, they may not be deemed harmful until a significant problem arises.

Factors contributing to human error include inadequate training, fatigue, demanding duty schedules, insistent corporate policies, lack of motivation, and poor adaptation to automation. To minimize the occurrence of accidents, awareness of the human factor must be disseminated, and this subject must be more thoroughly understood.

As a result of numerous maintenance-related accidents and incidents, Transport Canada identified twelve human factors that degrade the capacity of individuals to work safely. The aviation industry has adopted these twelve causes—widely known as the 'Dirty Dozen'—as a fundamental method for analyzing human error in maintenance. Identifying the symptoms of the Dirty Dozen is vital for preventing or controlling errors. The elements of the Dirty Dozen are as follows:

1) Lack of Communication
2) Complacency
3) Lack of Knowledge
4) Distraction
5) Lack of Teamwork
6) Fatigue
7) Lack of Resources
8) Pressure
9) Lack of Assertiveness
10) Stress

11) Lack of Awareness
12) Norms

2.1. Aircraft Maintenance Personnel

Nothing is as paramount as the sanctity of human life. It is a universal axiom that aviation remains the safest and most efficient mode of mass transportation. Although aircraft accidents are statistically rare, their occurrence profoundly undermines public confidence in the industry. Investigation into these accidents often reveals ostensibly minor errors that precipitate catastrophic consequences. Aircraft maintenance is a service fundamentally reliant on human performance. Regardless of the level of automation, technological sophistication, or economic resources, the human element remains the most vital component of the system, responsible for both executing maintenance and designing the very systems intended to mitigate error.

In the realm of aircraft maintenance, two primary professional roles predominate, both of which are critical to Flight Safety. These are the Airframe and Powerplant (Mechanical) Technician and the Avionics Technician. Airframe and Powerplant technicians are professionals responsible for line maintenance involving the aircraft structure, powerplants, and mechanical and electrical systems; they are also authorized to issue a Certificate of Release to Service (CRS). Furthermore, these technicians perform the removal and installation of Line Replaceable Units (LRUs) within avionics systems—tasks requiring simple functional tests—in strict accordance with civil aviation regulations. Conversely, the Avionics Technician manages the maintenance, repair, installation, and servicing of avionics and electrical systems, issues the CRS upon completion, and is authorized to perform mechanical removal and installation tasks during line maintenance as permitted by regulations.

Maintenance is a comprehensive term defining various tasks across diverse sectors and work environments. In aviation, maintenance activities encompass inspection, testing, measurement, adjustment, repair, fault diagnosis, servicing, lubrication, cleaning, and component replacement. Aircraft require maintenance at specific intervals or upon reaching defined flight-hour thresholds. Generally, aircraft maintenance is categorized into structural (fuselage, wings, landing gear), power systems (engines and propellers), and avionics (electrical systems and instrumentation). Routine maintenance rigorously involves corrosion control, component lubrication, inspections of fuel, hydraulic, and pneumatic systems, as well as wear and crack detection.

Broadly defined, aircraft maintenance is divided into 'Scheduled' and 'Unscheduled' maintenance. Unscheduled maintenance is performed in response to faults reported by the flight crew during operations. Scheduled maintenance, however, follows 'task cards' developed according to manufacturer directives and is performed at specific intervals based on flight hours, landing cycles, or calendar days. These are further classified as follows:

Line Maintenance (Type A Check): Includes tasks such as landing gear lubrication, engine fluid replenishment (oil, etc.), Integrated Drive Generator (IDG) lubrication, structural inspections for wear and friction, bird strike inspections, tire pressure checks, hydraulic servicing, and the review of damage entries in the technical Logbook.

Heavy Maintenance (Base Maintenance/Overhaul): Involves the removal of major components for corrosion, crack, and dent inspections; general and detailed visual inspections; component replacement; and modifications based on customer requirements.

Cabin Maintenance: Encompasses seat removal, armrest replacement, recline mechanism inspection, sidewall and lavatory (WC) panel replacement, and the installation of carpets, seat covers, and curtains. It also includes repairing door frame damage, replacing lighting (no-smoking, reading, sidewall lights), removing overhead bins, inspecting oxygen systems, maintaining cabin crew seats, removing/installing evacuation slides, and servicing galley/lavatory (wet area) surfaces.

Avionics Maintenance: Focuses on electronic systems vital for navigation, communication, radar, computer systems, and the Global Positioning System (GPS). This involves the inspection of electrical wiring, electronic test systems, and aircraft antennas.

Aircraft maintenance personnel are authorized individuals who perform scheduled maintenance, repairs, servicing, and inspections within standards set by regulatory authorities to ensure optimal aircraft performance. Obtaining specific licenses (Category A, B1, B2, C) is mandatory. The licensing process is governed by EASA (European Union Aviation Safety Agency) rules and regulations issued by the DGCA

(Directorate General of Civil Aviation / SHGM). The following regulatory acronyms are fundamental to the industry:

- SHY: Regulations issued by the Turkish DGCA.
- SHY-147: Regulation for Maintenance Training Organizations.
- SHY-145: Regulation for Approved Maintenance Organizations.
- SHY-66: Regulation for Certifying Staff.
- JAA / JAR: Joint Aviation Authorities and their respective regulations (precursor to EASA).
- Part-66 / Part-147: EASA standards for Certifying Staff and Training Organizations, respectively.
- Certificate of Release to Service (CRS): A document signed by certifying staff verifying that maintenance was completed in accordance with SHY-145/Part-145 standards.

Historically, JAR-66 was the prevailing standard in Europe; however, with the empowerment of EASA, Part-66 became the primary regulation. As Turkey is a member of the European aviation community and aligns with European standards, national regulations are harmonized with these benchmarks. In Turkey, SHY-66 was enacted on December 31, 2005, replacing SHD-T-35 to ensure compliance with EASA Part-66. Currently, there are 11 SHY-147 approved training organizations and 56 SHY-145 approved maintenance organizations in Turkey.

The DGCA defines the requirements for Certifying Staff via SHY-66. A certifying staff member is authorized to sign the CRS, certifying that maintenance was completed per SHY-145 standards. Technicians do not possess the authority to sign off on tasks as compliant with regulations unless explicitly granted a 'Certification Authorization' by the organization. The licensing categories are defined as follows:

Category A: Authorizes the holder to issue a CRS following minor scheduled line maintenance and simple defect rectification performed personally by the holder.

Category B1: Authorizes the holder to issue a CRS following line maintenance on the aircraft structure, powerplants, and mechanical/electrical systems, including fault rectification and the replacement/testing of avionics LRUs.

Category B2: Authorizes the holder to issue a CRS following line maintenance and fault rectification on avionics and electrical systems.

Category C: Authorizes the holder to issue a single CRS for the entire aircraft following the completion of base maintenance (overhaul). While Category A and B technicians sign for their specific tasks, the Category C certifying staff oversees the entire package to ensure regulatory compliance before final release.

2.2. Maintenance-Related Errors and Accidents

One of the fundamental causes of aviation accidents is the occurrence of maintenance-related failures and their subsequent progression into catastrophic crashes. In 2007, EASA analyzed global commercial aircraft accidents between 1990 and 2006, identifying maintenance as the primary cause in 8% of these occurrences. Furthermore, between 1999 and 2008, it was determined that 26.7% of all fatal accidents were maintenance-related. According to IATA data, 20% to 40% of aircraft accidents occurring between 2003 and 2008 resulted from deficient maintenance processes, either as the primary root cause or the initial link in the accident chain. IATA's safety report for the period of 2009–2013 concluded that maintenance events accounted for an average of 10% of the threats leading to 432 aircraft accidents.

Data from 232 commercial jet accidents analyzed by Boeing regarding accident prevention opportunities revealed that 20% of these occurrences involved a maintenance or inspection action. The United States National Transportation Safety Board (NTSB) reported that inadequate maintenance played a role in 7 out of 14 (50%) recent airline accidents. The NTSB further noted that as advancements in aircraft design and pilot training mitigate risks in those domains, the proportion of accidents attributed to those factors has declined; consequently, the relative rate of accidents attributed to inadequate maintenance has risen. Maintenance errors not only jeopardize flight safety but also inflict significant economic losses on the aviation industry through operational delays and component damage. Figure 4 shows the statistical data published by Boeing regarding the causes of damaged aircraft accidents that occurred between 1996 and 2005.

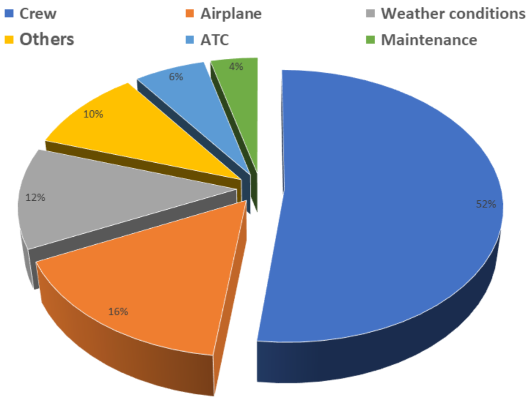


Figure 4. The main causes of damaged aircraft accidents that occurred between 1996 and 2005. (Nazlıoglu, 2014).

According to an Airbus survey conducted in 2006, the most prevalent consequence of maintenance-related events in airline operations is damage to components or the aircraft itself during the maintenance process. This is followed, respectively, by incorrect installation (referring to the orientation or positioning of a part) and incomplete assembly errors. Consistent with broader research into maintenance failures, incorrect and incomplete installations frequently predominate the list of occurrences. Analysis of extant literature identifies 'time pressure' as the primary driver for incorrect installation, followed by a 'lack of technical knowledge, skill, or qualification' and 'inadequate training.' Similarly, for cases of incomplete assembly, 'time pressure' remains the most plausible underlying cause, followed by 'lack of technical knowledge,' 'communication failures,' and 'fatigue.'

Historical maintenance-related accident case studies provide critical insights into these failures. The use of unapproved engine replacement procedures led to the crash of American Airlines Flight 191 (DC-10). In the case of Japan Airlines Flight 123 (B747), an improper modification of the aft pressure bulkhead resulted in a catastrophic failure, leading to the loss of 524 lives. The Aloha Airlines Flight 243 (B737) accident demonstrated how metal fatigue combined with deficient inspection protocols can culminate in a significant in-flight structural failure. In the British Airways Flight 5390 (BAC 1-11) incident, the installation of the cockpit windshield with inappropriate fasteners led to a near-fatal event where the captain was partially ejected from the aircraft. Finally, the Continental Express Flight 2574 (Embraer 120) crash was attributed to missing fasteners on the horizontal stabilizer's de-icing boot, which resulted in a loss of control and subsequent impact.

3. Method

The primary objective of this research proposal is to focus on the preventive measures aircraft maintenance personnel can adopt against potential human-induced errors, the competency levels of these personnel relative to their training, the safety protocols they implement, and their procedural compliance (adherence to technical manuals). Ultimately, this study aims to ensure that maintenance personnel possess the requisite knowledge, skills, and competencies to perform high-quality maintenance, adopt safety measures that minimize error propensity, maintain a constant focus on Human Factors principles, and execute maintenance in accordance with established standards. Furthermore, it is intended that the results of this survey will foster an increase in effort and achieve the desired levels of maintenance performance.

The survey instrument developed for this study comprises three distinct sections. The first section gathers demographic data, industry experience, information regarding the institution where the aircraft maintenance training was received, and details of the current department of employment. The second section consists of inquiries related to the professional aircraft maintenance training received by the participants. The third section focuses on questions regarding employee performance. A 5-point Likert scale was utilized for the second and third sections. The response options were defined as: '1. Strongly Disagree, 2. Disagree, 3. Somewhat Agree, 4. Agree, and 5. Strongly Agree.' The survey was administered to relevant aircraft maintenance personnel, and SPSS for Windows was employed for the statistical analysis of the acquired data.

4. Findings

Within the scope of this research, survey forms were distributed to members of the Aircraft Maintenance Technicians Association (UTED), the Civil Aviation Alumni Association, and candidates participating in the SHY-147 aircraft maintenance training examinations. A total of 83 responses were received. Following an eligibility review by the researcher, 72 valid survey forms from participants with formal maintenance training were included in the research population for evaluation. According to the analyzed results, the gender distribution of the participants is shown in Table 1.

Table 1. Gender distribution of participants.

		Gender			
		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	Male	66	91,7	91,7	91,7
	Female	6	8,3	8,3	100,0
	Total	72	100,0	100,0	

The participants' years of work experience are given in Table 2. The highest percentage of participants, at 47.2%, are employees with 10 years or more of experience.

Table 2. Distribution of participants' work experience duration.

		Aircraft Maintenance Experience			
		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	0-3 Years	28	38,9	38,9	38,9
	4-6 Years	2	2,8	2,8	41,7
	7-10 Years	8	11,1	11,1	52,8
	10 years +	34	47,2	47,2	100,0
	Total	72	100,0	100,0	

As shown in Table 3, 68.1% of the participants hold a bachelor's degree, 19.4% hold an associate's degree, and 8.3% received aircraft maintenance training during their high school years.

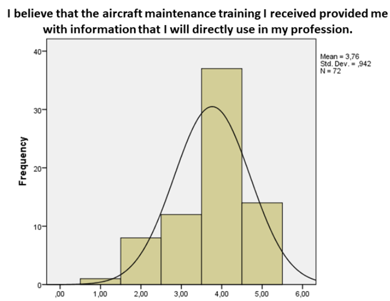
Table 3. Distribution of participants' educational levels

		Aircraft maintenance training			
		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	Bachelor	49	68,1	71,0	71,0
	Associate Degree	14	19,4	20,3	91,3
	High School	6	8,3	8,7	100,0
	Total	69	95,8	100,0	
Missing	System	3	4,2		
Total		72	100,0		

Table 4 shows the departments where the participants work. 58.3% of participants work in mechanics, 19.4% in avionics, and 22.2% in workshops.

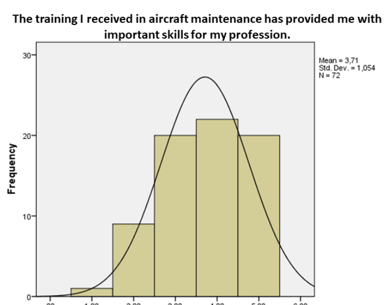
Table 4. The distribution of departments where participants work in aircraft maintenance.

		Aircraft maintenance department			
		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	Mechanics	42	58,3	58,3	58,3
	Avionics	14	19,4	19,4	77,8
	Workshops	16	22,2	22,2	100,0
	Total	72	100,0	100,0	



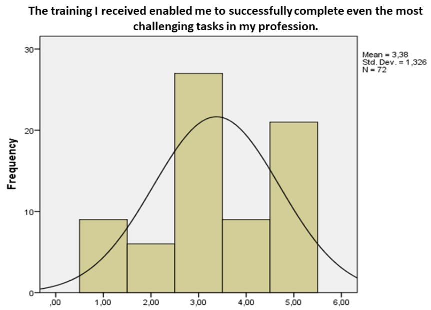
Graph 1. Frequency and participation rate results for the sixth question.

The Graph 1 shows that the mean (mean = 3.76) indicates satisfaction above the expected threshold (the neutral point of 3.00). This value, with a standard deviation (Std. Dev. = 0.942) below one, suggests that the responses are relatively close and there is no significant polarization among participants. The data demonstrates that aircraft maintenance training aligns with industry needs and that employees are able to apply the knowledge they gain in their professional lives. The data exhibits a "negatively skewed" trend, which is desirable in measures of success or satisfaction.



Graph 2. Frequency and participation rate results for the seventh question.

The Graph 2 shows that participants generally agree that training improves skills, with a mean of 3.71. A standard deviation (Std. Dev. = 1.054) above one indicates greater diversity in opinions. In other words, the group is slightly more divided regarding the level of skill improvement achieved through training compared to the previous graph.

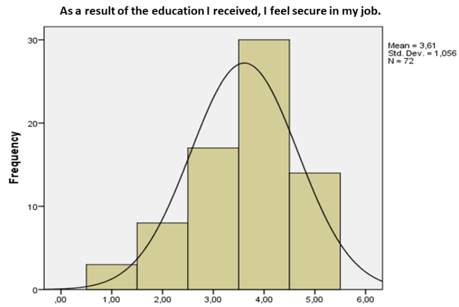


Graph 3. Frequency and participation rate results for the eighth question.

In the Graph 3, the mean (Mean = 3.38) is the lowest among the other items. While participants are convinced that the training "improves skills" (3.71), they are more cautious about its ability to "perform the most challenging tasks" (3.38). The standard deviation (Std. Dev. = 1.326) in this graph is quite high. This indicates significant disagreement among participants on this item. While some believe the training is sufficient even for very difficult tasks (those who scored 5.00), a significant group believes it is insufficient (those who scored 1.00 and 2.00).

Graph 4. Frequency and participation rate results for the ninth question

The Graph 4 shows that participants generally agree that the training improved their performance, with an arithmetic mean (Mean = 3.68). This graph has a low standard deviation (Std. Dev. = 0.869). The responses are very close together, and there is no significant polarization.

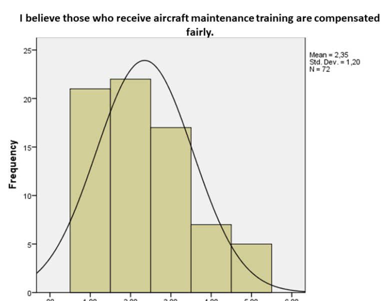


Graph 5. Frequency and participation rate results for the tenth question.

The Graph 5 shows that, with a mean of 3.61, participants generally feel more secure in their jobs after receiving the training. The standard deviation (Std. Dev. = 1.056) indicates a moderate distribution of opinions.

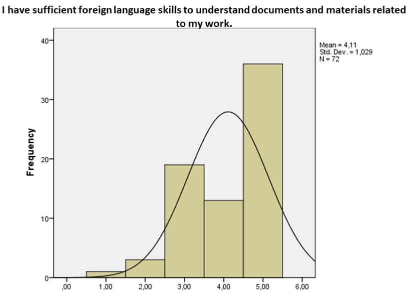
Graph 6. Frequency and participation rate results for the eleventh question.

In the Graph 6, participants gave moderate support (between undecided and agree) to this statement, with an arithmetic mean of (3.40). This score indicates that education is seen as an important factor, but there is no complete consensus that it is the only way. A standard deviation greater than one (Std. Dev. = 1.146) suggests that participants have differing opinions on the absolute impact of education on performance.



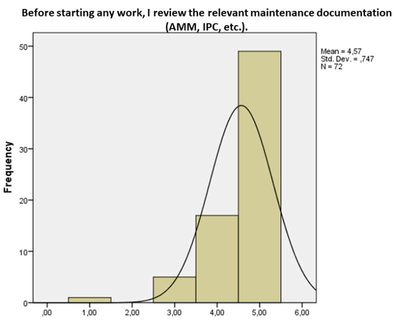
Graph 7. Frequency and participation rate results for the twelfth question.

The Graph 7 shows that participants generally responded with "Disagree" to this statement, with a very low mean (Mean = 2.35). Unlike all other graphs with a right-skewed (positive skew) distribution, the clustering in this graph is on the left side (lower scores). The standard deviation (Std. Dev. = 1.20) is quite high, indicating that participants' levels of dissatisfaction with compensation varied, but the majority converged on negative.



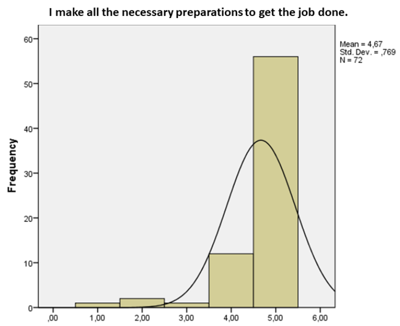
Graph 8. Frequency and participation rate results for the thirteenth question.

The Graph 8 shows that a large majority of participants are confident in their foreign language skills, with a high mean value (Mean = 4.11). This value, above 4 on a scale of 5, demonstrates that the group exhibits a strong stance on language proficiency, ranging from "Agree" to "Strongly Agree." While the standard deviation (Std. Dev. = 1.029) is reasonable given that very few individuals scored below 5.00, although the responses are concentrated around that point.



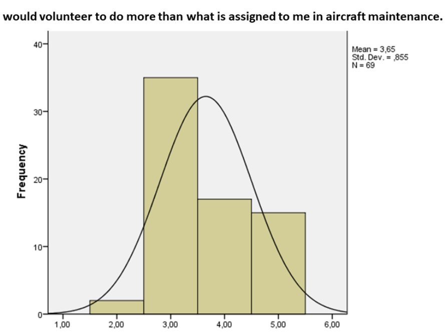
Graph 9. Frequency and participation rate results for the fourteenth question.

The Graph 9 shows that the arithmetic mean (Mean = 4.57) indicates that almost all participants on a 5-point scale said "Strongly Agree" to this statement. The low standard deviation (Std. Dev. = 0.747) proves that the group was in complete agreement on this issue. There was no significant disagreement among participants regarding document review habits.



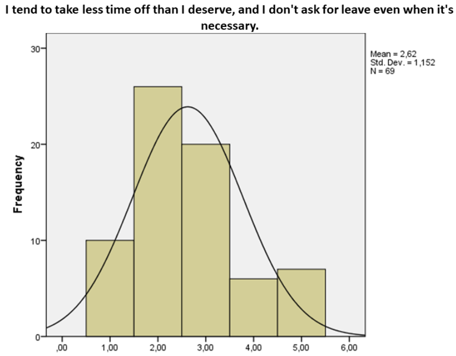
Graph 10. Frequency and participation rate results for the fifteenth question.

The Graph 10 shows that the very high mean (Mean = 4.67) indicates that almost all participants reported having impeccable discipline in job preparation. The very close standard deviation (0.769) of the responses proves that this disciplined behavior has become a general culture within the group and does not vary much from person to person.



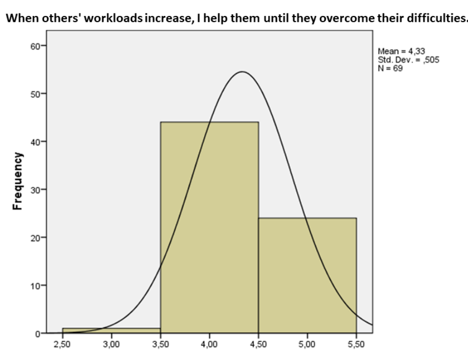
Graph 11. Frequency and participation rate results for the sixteenth question.

The Graph 11 shows that participants generally exhibit a willingness to go beyond the given tasks, with an arithmetic mean (Mean = 3.65). This score ranges from "Undecided" to "Agree," indicating a tendency towards pro-social behavior within the group. The highest frequency (Mode) is 3.00 (Undecided), suggesting that approximately half of the group is cautious about "going beyond the task" or evaluates this situation according to the job description. The number of participants for this question was 69, compared to 72 for the other questions. Three participants chose not to answer this question.



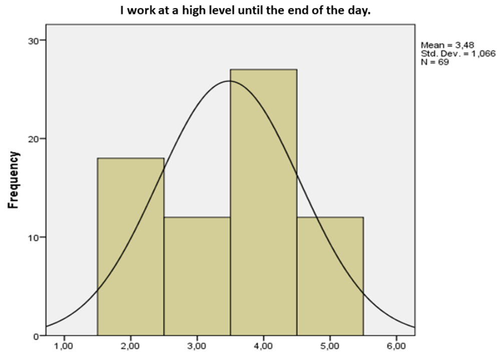
Graph 12. Frequency and participation rate results for the seventeenth question.

The Graph 12 shows that the arithmetic mean (Mean = 2.62) indicates that the group exhibits a stance between "Disagree" and "Undecided," but closer to the negative side. This means that the majority of staff are not hesitant to take leave when necessary. A standard deviation (Std. Dev. = 1.152) greater than one suggests that staff have differing attitudes towards taking leave. A small group has made not taking leave a rule (5.00 points), while a larger group favors using their leave entitlements. As with the previous graph, 69 people responded to this question.



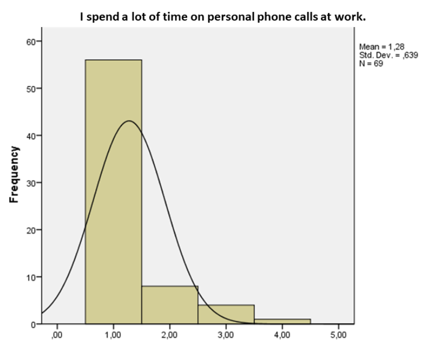
Graph 13. Frequency and participation rate results for the eighteenth question.

The Graph 13 shows that participants have a very high propensity to help colleagues with increasing workloads, with an arithmetic mean (Mean = 4.33). A score of 4.33 on a 5-point scale indicates that the group generally holds a position between "Agree" and "Strongly Agree." The standard deviation (Std. Dev. = 0.505) remains very low. This suggests that participants are in near complete agreement on helping and that the group exhibits a very homogeneous structure in this regard.



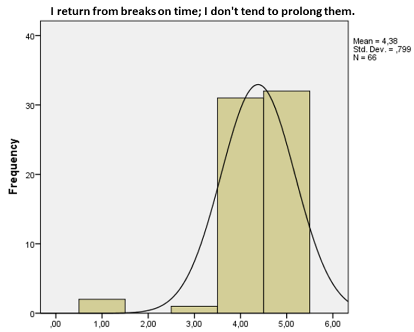
Graph 14. Frequency and participation rate results for the nineteenth question.

The Graph 14 shows that participants exhibit a slightly above-average (3.00) tendency to maintain their performance until the end of the day, with an arithmetic mean (Mean = 3.48). This value indicates that the staff are generally hardworking, but may experience some performance decline towards the end of the workday, or that the staff are cautious in this regard. A standard deviation (Std. Dev. = 1.066) greater than one indicates that the energy and performance levels of the participants differed significantly at the end of the day.



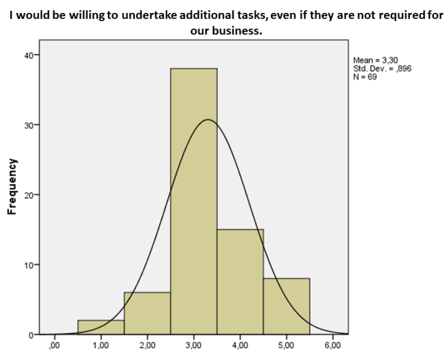
Graph 15. Frequency and participation rate results for question twentieth.

The Graph 15 shows that the arithmetic mean (Mean = 1.28) indicates that the group strongly "Disagrees" with this statement. It appears that participants focus on their duties rather than personal matters during working hours. The relatively low standard deviation (Std. Dev. = 0.639) suggests that the staff share a common culture regarding this professional attitude.



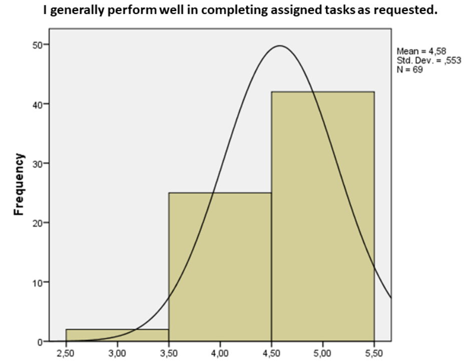
Graph 16. Frequency and participation rate results for question twenty-one.

The Graph 16 shows that participants demonstrated a very high level of adherence to break times, with an arithmetic mean (Mean = 4.38). The low standard deviation (Std. Dev. = 0.799) and the similarity of the responses indicate that time discipline has become a general work culture within the team.



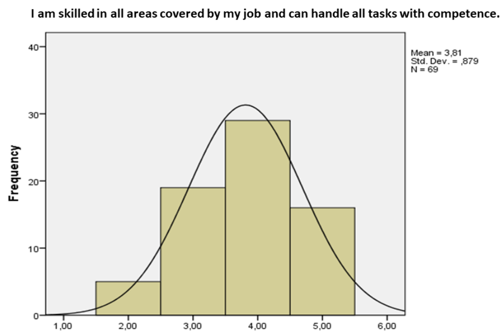
Graph 17. Frequency and participation rate results for question twenty-two.

In the Graph 17, participants show a moderate level of willingness, slightly above the "Undecided" level (3.00), with an arithmetic mean (Mean = 3.30). This score indicates that personnel are not very enthusiastic about going beyond their job descriptions, but they do not completely reject it either. The low standard deviation (0.896) suggests that the group is quite close to each other in this "detached/undecided" attitude.



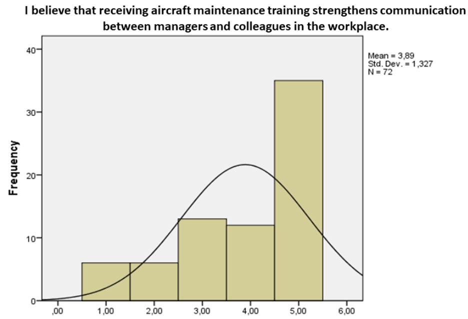
Graph 18. Frequency and participation rate results for question twenty-third.

The Graph 18 shows that participants rate their performance in completing their tasks as quite high, with an arithmetic mean (Mean = 4.58). The very low standard deviation (Std. Dev. = 0.553) demonstrates complete agreement among participants regarding their positive perception of their own performance. The analysis was conducted on 69 individuals.



Graph 19. Frequency and participation rate results for question twenty-four.

In the Graph 19, the arithmetic mean (Mean = 3.81) indicates that the participants' overall self-confidence level is quite high. This value is close to the "Agree" level (4.00) and shows that the personnel feel they are in control of their work. The low standard deviation (Std. Dev. = 0.879) proves that the participants' perceptions of their own abilities are quite similar. The analysis was conducted on 69 people.



Graph 20. Frequency and participation rate results for question twenty-five.

In the Graph 20, participants generally agree that the training strengthened communication between both managers and colleagues, with an arithmetic mean (Mean = 3.89). The standard deviation (1.327) indicates a high degree of disagreement among participants regarding the communication effect.

The study shows that Alpha is affected by sample size and number of items. When we examined the internal factorization of a factor, we concluded that a value below 0.7 indicates reliability, and Cronbach's Alpha of 0.745 is sufficient. These values are shown in Table 5.

Table 5. Values of reliability statistics

Reliability Statistics	
Cronbach's Alpha	N of Items
,745	20

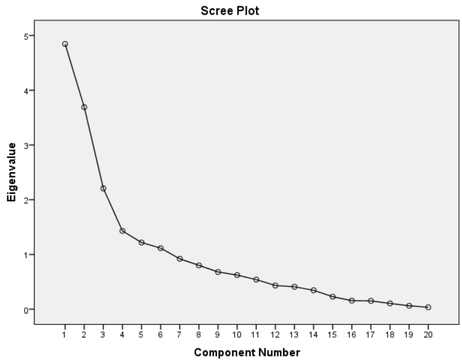
Table 6 shows that the p-value for the KMO Bartlett test is 0.479.

Table 6. KMO Bartlett test results

KMO and Bartlett's Test		
Kaiser-Meyer-Olkin Measure of Sampling Adequacy.		,479
Bartlett's Test of Sphericity	Approx. Chi-Square	795,002
	df	190
	Sig.	,000

A rotated component matrix was created and a Varimax 25 rotation was applied. In calculating factor loadings within the scope of the research, only those with Eigenvalues greater than 1 were used. Examination of the

Scree Plot and Principal Component Analysis (PCA) revealed a six-factor structure. Scree Plot and PCA analysis are shown in Graph 21.



Graph 21. Scree Plot. Principal Component Analysis results.

The rotated component matrix is shown in the Table 7.

Table 7. Rotated component matrix results

Rotated Component Matrix[a]						
Survey Items	Components					
	1	2	3	4	5	6
I believe that I learned information directly used in my profession during the aircraft maintenance training I received.	,911					
The training I received regarding aircraft maintenance provided me with significant skills for my profession.	,902					
The training I received improved my professional performance.	,804					
The training I received enabled me to successfully complete even the most difficult tasks in my profession.	,663					
As a result of the training I received, I feel confident about my job.	,592					
I am competent in all areas covered by my job; I handle all tasks with expertise.		,807				
I return from breaks on time; I do not tend to extend them.		,680				

I work with high performance until the end of the day.		,677				
When others' workload increases, I help them until they overcome the difficulties.			,749			
I volunteer to do more than the assigned task in aircraft maintenance.			,682			
I am willing to perform extra duties even if not strictly necessary for our organization.			,673			
I think the only way to increase performance in my profession is to receive aircraft maintenance training.			,580			
Before starting a task, I examine the relevant maintenance documents (AMM, IPC, etc.).				,926		
I possess sufficient foreign language skills to understand documents and records related to my job.				,727		
I fully complete all necessary preparations before performing a task.				,699		
I believe that fair compensation is provided to those who receive aircraft maintenance training.					,812	
I think that receiving aircraft maintenance training strengthens communication between managers and colleagues in the workplace.					,590	
I generally display good performance to fulfill assigned duties in the desired manner.						,702
I spend long periods on personal phone calls at my workplace.						-,598
I tend to use less leave than I am entitled to; I do not take leave even if necessary.						-,469
Extraction Method: Principal Component Analysis. Rotation Method: Varimax with Kaiser Normalization. a. Rotation converged in 11 iterations.						

Factor Structure

Factor 1: Training Effectiveness and Professional Competence

I believe the aircraft maintenance training I received provided me with knowledge that I apply directly to my profession.The training I received regarding aircraft maintenance equipped me with essential professional skills.My training has facilitated an increase in my professional performance.The education I received enabled me to successfully complete even the most challenging professional tasks.As a result of my training, I feel confident and secure in my work performance.

Factor 2: Self-Efficacy and Work Discipline

I am competent in all domains of my job and handle all tasks with mastery.I return from breaks on time and do not tend to extend them.I maintain high performance levels throughout the workday until completion.

Factor 3: Organizational Citizenship and Altruism

When the workload of others increases, I assist them until the difficulties are overcome. I volunteer to go beyond the assigned tasks in aircraft maintenance. I am willing to perform additional tasks, even if they are not strictly required by the organization. I believe that receiving aircraft maintenance training is the primary way to enhance professional performance.

Factor 4: Technical Readiness and Linguistic Proficiency

Prior to commencing a task, I thoroughly review the relevant maintenance documentation (e.g., AMM, IPC). I possess sufficient foreign language proficiency to comprehend job-related documents and manuals. I perform all necessary preparations comprehensively before executing a task.

Factor 5: Perception of Equity and Organizational Communication

I believe that those who receive aircraft maintenance training are compensated with a fair wage. I believe that receiving aircraft maintenance training strengthens communication between managers and colleagues in the workplace.

Factor 6: Task Performance and Work Habits

I generally exhibit high performance in fulfilling assigned tasks as required. I spend significant amounts of time on personal phone calls at the workplace. (Note: Typically a reverse-scored item in performance scales). I tend to use less leave than I am entitled to, and I refrain from taking time off even when it is necessary.

5. CONCLUSION AND RECOMMENDATIONS

- Participants confirmed a high degree of congruence between the training curriculum and actual professional practice.
- The study reveals that participants exhibit an exemplary level of discipline regarding comprehensive work preparation and the meticulous review of maintenance documentation prior to task commencement.
- The utilization of foundational technical safety documents, specifically the AMM (Aircraft Maintenance Manual) and IPC (Illustrated Parts Catalog), has evolved into an uncompromising organizational culture within the maintenance teams.
- This rigorous adherence to pre-task preparation and documentation discipline serves as empirical evidence that operational error risks are being maintained at a minimum level.
- There is a clear consensus among participants that the training has equipped them with vital professional skills and significantly enhanced their operational performance.
- Participants strongly asserted a level of foreign language proficiency sufficient for the thorough comprehension of complex technical documentation.
- The vast majority of participants perceive themselves as highly competent across all work domains and report generally superior performance levels.
- The marked propensity to assist colleagues with increasing workloads demonstrates a robust culture of mutual aid and high levels of Organizational Citizenship Behavior (OCB).

- Beyond technical skill acquisition, the training offers significant social utility by strengthening communication channels between management and peers.
- The weakest link identified in the research is the perception of fair remuneration. The divergence between high technical discipline and low economic satisfaction represents the primary risk factor for personnel retention.
- Despite high success rates in core duties, self-confidence and consensus regarding the mastery of the most complex tasks are comparatively lower; this highlights a specific need for advanced technical specialization training.
- While personnel perform their primary professional duties flawlessly, they exhibit a more reserved attitude toward undertaking auxiliary tasks or forfeiting leave, a trend likely attributable to the perception of inadequate compensation.
- High scores in adhering to break schedules and avoiding personal business during work hours indicate an excellent level of professional work ethics among the personnel.
- While the training is highly effective in imparting core competencies, its efficacy regarding complex and high-pressure operational processes warrants further enhancement.
- It is recommended that the training program maintain its success in standard operations while being reinforced with complex task scenarios and advanced problem-solving modules to cultivate a holistic sense of competence.
- Finally, a strategic review of remuneration policies is essential to ensure the long-term sustainability of training efficiency and organizational commitment.

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DETERMINATION AND EVALUATION OF NOISE EXPOSURE OF WORKSHOPS IN AIRCRAFT MAINTENANCE TECHNICIAN TRAINING INSTITUTIONS

İbrahim Güçlü*, Sinem Kahvecioğlu**

Abstract

Workshops in educational institutions that train aircraft maintenance technicians are among the most intensive areas of the training process undertaken there. These environments contain numerous components such as hand tools, pneumatic systems, engine and accessory test equipment, and sheet metal processing equipment, which generate noise at various levels. These noise levels, which increase continuously or intermittently, have become a significant occupational health and safety issue for both students and academics and staff. Accurately interpreting noise-related risks is not limited to protecting hearing health; it can also affect attention, communication, and educational performance. Therefore, measuring noise levels in workshops within these institutions and evaluating them using scientific methods is crucial for a sustainable and healthy educational environment. In this context, the study should be considered not merely as a measurement for compliance with relevant legislation, but as a contribution aimed at strengthening the safety culture in maintenance training conducted under SHT-147. It is expected that the results of the study will offer opportunities for improvement in similar educational institutions and generate practical recommendations for noise control.

Keywords: Aircraft Maintenance Training, Workshop Noise, Noise Exposure, Aviation

Introduction

Since the Industrial Revolution, the accelerated use of machinery in production processes has contributed to increased efficiency and comfort in many areas of daily life. One striking example of this contribution is the

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technological advances in aviation, which have made aeroplanes safer, more comfortable and more accessible to people. The growing interest in air travel in recent years has led to the expansion of airline fleets and, consequently, an increased need for qualified personnel. At this point, aircraft maintenance technicians play a critical role in ensuring the operational continuity of flights and maintaining flight safety. To meet this critical need in aviation, universities aim to train technical personnel through programmes such as Airframe and Powerplant Maintenance, Avionics, and Aircraft Technology.

According to the instructions published by the General Directorate, students in these programmes must complete a certain level of practical training in addition to theoretical courses during their education. As practical training takes place in workshop environments where maintenance and repair activities are carried out, students may encounter physical difficulties similar to those encountered in real working conditions. Among these conditions, noise, workshop equipment and the activities carried out are significant risk factors. Repeated and prolonged exposure to noise can adversely affect students' hearing health over time; it can also indirectly lead to negative consequences on attention, communication, and safe working behaviour. Therefore, determining the level of noise exposure in workshops where practical training is conducted and assessing potential risks is important both to protect students' health and to provide a reliable learning environment.

Any unwanted sound that causes discomfort to humans is defined as noise(Pugh et al., 2007). With advancing industrialization, the incorporation of complex equipment into daily life, while facilitating life, is also one of the reasons for increased noise levels. The widespread use of vehicles and urban public transportation, the increased use of electronic devices in homes due to the convenience provided by technological household appliances, and the equipment used in industry and workshops constitute the main sources of noise today. Training sets and equipment used in areas belonging to educational institutions where aircraft maintenance technicians are trained, as well as indirect environmental factors, also stand out as sources of noise. Especially the potential risks of occupational diseases caused by long-term noise exposure become apparent. Noise exposure should not be considered solely in terms of hearing loss. Noise occurring in work environments also leads to the risk of other disorders in the body, primarily psychological disorders such as stress and anxiety (Moore, 2003). Therefore, it is important to prevent noise exposure and to take the necessary precautions in educational institutions that train aircraft maintenance technicians.

AIRCRAFT MAINTENANCE TECHNICIAN

An Aircraft Maintenance Technician is personnel licensed by the aviation authority of the relevant country and performs maintenance and repair by inspecting the airframe structures, engines, electronic, and avionics systems of aircraft. Depending on the field of training, they are able to perform maintenance on applicable aircraft in accordance with the license categories provided in Table 1(URL-1).

Table 2.License Categories

License Category	Definition
Category A	Line Maintenance Technician
Category B1	Aircraft Maintenance Technician (Mechanical)
Category B2	Aircraft Maintenance Technician (Avionics)
Category C	Aircraft Base Maintenance Technician

Category A aircraft maintenance license authorizes the issuance of a certificate of release to service following scheduled minor line maintenance and the rectification of simple faults, provided that the maintenance limitations specified in the regulation are complied with.

Category B1 aircraft maintenance license grants authorization to perform maintenance related to the aircraft structure, power unit, mechanical and electrical systems and, except for fault diagnosis and rectification procedures, to carry out only simple tests on avionics systems for the purpose of checking their operational status. In addition, the Category B1 license also includes the maintenance authorizations of the Category A license.

Category B2 aircraft maintenance license grants authorization to perform maintenance on avionics and electrical systems and to carry out only simple tests on power systems and mechanical systems solely for the purpose of checking their operational status.

The Category C aircraft maintenance license grants its holder the authority to issue a certificate of release to service following base maintenance performed on the aircraft. The privileges of the Category C aircraft maintenance license apply to the aircraft as a whole.

The Directorate General of Civil Aviation (DGCA) requires a set of conditions from training institutions that educate technicians in order to train technicians, and it grants authorizations—such as recognized school or approved training organization—to training institutions that are able to fulfill these conditions.

Approved Training Organization Certificate

In Türkiye, the Directorate General of Civil Aviation (DGCA) sets specific requirements to ensure the adequacy of aircraft maintenance technician training and, accordingly, authorizes training institutions with the SHT-147 certificate. In order for a training institution to obtain authorization, the facility requirements specified by DGCA in the regulation are stated as follows(URL-2):

a. The size and structure of the facilities shall be suitable for protection from all adverse weather conditions and for the proper conduct of all planned training and examinations on any designated day without being affected by weather conditions.

b. A suitable location that is separate from other facilities and completely enclosed shall be provided for the delivery of theoretical training and the conduct of knowledge examinations.

1. During any theoretical training course, the number of students receiving this training shall not exceed 28.

2. The size of the area allocated for examinations shall be such that no student can read another student’s paper or computer screen from their position during the examination.

c. The classroom and examination area(s) specified under paragraph (b) shall be free from distracting and disturbing elements that would impair students’ concentration on their own studies or examinations.

d. During the basic training course, basic training workshops and/or maintenance facilities separate from the theoretical classrooms shall be provided for practical training in accordance with the planned training. However, if the organization is unable to provide such facilities, cooperation may be established with another organization to provide the relevant workshops and/or maintenance facilities, and a written agreement specifying the conditions regarding access to and use of the facilities shall be concluded with that organization. Access by the Directorate General to the said facilities shall be ensured, and this matter shall also be explicitly stated in the written agreement.

e. If the training concerned is aircraft type practical training or task training, it is necessary to ensure that the training organization has access to the relevant aircraft type and/or components. Where it is demonstrated that synthetic training devices provide sufficient training standards, synthetic training devices may be utilized.

f. During any practical training, the number of students shall not exceed 15 per practical instructor or assessor.

g. Office facilities shall be provided for instructors, theoretical examination preparers, and practical assessors to allow them to prepare for their duties without being disturbed or distracted.

h. Training and examination records shall be stored under secure conditions in accordance with IR 147.A.125.

i. A library containing all technical materials appropriate to the scope and level of the approved training shall be provided.

The storage conditions specified in accordance with IR 147.A.125 are as follows:

a. The organization is required to keep training, examination, and assessment records for each student indefinitely.

b. The storage environment shall be safe and secure against damage or theft of documents.

c. Provided that adequate security is ensured, the storage environment and the office may be combined.

In training organizations authorized by DCGA, in accordance with the conditions specified in paragraphs (c) and (d) of the facility requirements, students are required to receive practical training in workshops. This, in turn, gives rise to exposure to noise pollution in workshops and the necessity of taking precautions.

Noıse Pollutıon Occurrıng In Workshops

Many studies have reported that educational institutions often have noisy learning environments and that noise is progressively worsening (Persson et al., 2013). The relationship between noise in schools and educational activities has direct negative effects on learning because it increases distraction and discomfort. According to various studies, excessive noise is detrimental to teaching and learning, as it distracts students, reduces their attention span and cognitive abilities, makes it difficult for them to hear and understand their teachers, and diminishes their sense of hearing (Woolner et al., 2010; de Almeida Filho et al., 2012).

In the literature, when the main studies conducted in educational institutions are examined, it has been reported that on the campus of the Federal University of Juiz de Fora (UFJF) in Brazil, indoor and outdoor noise levels varied between 44 and 70 dB. The researchers not only determined noise through measurement devices but also combined two approaches, quantitative and qualitative, by using questionnaires to investigate how individuals were affected by this noise. On-site sound measurements were conducted at 32 outdoor and 11 indoor locations within the campus. A questionnaire was administered to 140 volunteer individuals (students, academic/staff), and the measurements were compared with the Brazilian standards NBR 10.151 / NBR 10.152 and WHO recommendations (de Souza et al, 2020).

At Atatürk University campus (Erzurum), noise pollution was measured and evaluated at a total of 13 measurement points, primarily at the main locations with dense vehicle traffic, and across morning, noon, and evening time intervals. The findings indicate that the average noise level across the campus was 62.70 dB(A), which remained above the level of 55 dB(A) used in the study as the permissible average value (Ozer et al., 2014).

A study was conducted at the University of Uyo in Nigeria to examine noise pollution within the Town Campus, drawing attention to the widespread use of generators due to power outages. The researchers quantitatively determined noise levels on campus through measurements and, using questionnaire data, classified the main sources of noise. In the study, noise measurements were conducted using a digital sound level meter in the dB(A) band, and measurements were taken at different points of the campus (administrative building, laboratory, library, business centers, etc.). In total, 127 measurement records were evaluated and the data were analyzed in Excel. The analysis of the measurements reported by the researchers indicated that the overall noise level increased markedly toward noon and reached its highest value of 89.5 dB(A) between 11:00 and 12:00. In addition, the noise range generated by the generators was reported to be approximately 81.1–95.2 dB(A). According to the survey results, the most dominant sources of noise were distributed as follows: generators at 42%, students at 37%, vehicles at 19%, and business centers at 2% (Obot & Ibanga, 2013).

A study investigating indoor noise quality was conducted in the Environmental Engineering Department building at Babylon University (Hillah) in Iraq. The researchers selected four zones, namely four classroom lecture rooms, the student corridor, the faculty corridor, and the reception area, and interpreted the results by conducting assessments spread over the period between August 2020 and August 2021. Measurements were obtained between 09:00 and 17:00 during the day, with multiple repetitions at different time intervals in each space. Based on the mean values obtained, linear regression was applied to examine the relationships among the selected areas. In all investigated areas, background noise levels were found to be above the reference level of 50 dB, and it was stated that the acoustic environment within the building required improvement (Al-Isawi et al., 2022).

In order for education to be conducted under appropriate physical conditions and for interpersonal communication to be carried out in a healthy manner, it is important to ensure appropriate acoustic conditions in workshops. When evaluating noise occurring in classrooms, attention should be paid to the following factors:

• Duration of the measurement (ISO, 1996)

• The characteristics and position of the microphone/microphones in the room(ISO, 1996)

• Data analysis using spectral or single-number descriptors (ISO,1996; BB93, 2014; Crandell, 1995).

The sources of noise occurring in classrooms may arise from different factors. Examples include sounds originating from the external environment, environmental sounds resulting from students' communication and physical movements, and sounds generated depending on the tools and equipment used during the lesson.

Noise Sources Present in Workshops

It was previously stated that approved training institutions that train aircraft maintenance technicians are required to include practical courses. The practical courses conducted in these institutions are carried out particularly for the purpose of gaining training on parts that can be used in aircraft structures, such as disassembly-assembly, part design, cutting, filing, drilling, and riveting. While these practical activities are being performed, noise levels vary depending on the hand tools and equipment used. For example, due to the riveting gun (Figure 1) used during the riveting process, the resulting noise level exceeds the permitted noise limits. For this reason, it is specifically stated that protective earmuffs should be worn during riveting.

Figure 10. Pneumatic Riveting Gun Set

Other hand tools used in the workshops of educational institutions that may cause noise can generally be listed as drills, hammers, mallets, files, and sheet metal cutting benches. Students working with these and similar tools must wear their protective equipment in order to avoid exposure to adverse factors, and attention should be paid in workshops to precautions against these adverse factors.

Aim And Method

In the practice building where the study was conducted, there are a total of three workshops: Structural 1, Structural 2, and the engine workshop.

The study was carried out in accordance with the limit of 15 students permitted for the practical course as required by the SHT-147 instructions. The part was produced in two groups, and two riveting guns were used with the necessary protective equipment and precautions in place. The noise exposure values were recorded and specified throughout one lesson hour during which the riveting process was performed. The practical training workshop (Figure 2) was conducted in accordance with the requirements of ISO 1996, and by fixing the microphone at a height of 1.5 m from the ground and at distances of 1 m, 2 m, 3 m, and 4 m from the area where the work would be carried out, the distance-dependent variation of the noise level to which individuals were exposed at close range during the work was evaluated.

Figure 11.The Structural Workshop Where the Study was Conducted.

As the microphone selection, the Magicvoice JH-043 mobile-compatible device, which has features including high-sensitivity audio recording, a clip-on design to enable fixation, and noise reduction to minimize interference sounds, was preferred (Figure 3).

Figure 12.Magicvoice JH-043

During the measurement, all workshop doors were closed, and the measurement was carried out without environmental factors such as wind during riveting. For the measurement, noise measurements were evaluated over one lesson hour in three different stages:

• Noise measurement caused by student voices without using the riveting gun

• Noise measurement performed using one riveting gun

• Noise measurement performed using two riveting guns

For the measurement procedure, the “dB Meter” measurement application, which enables precise measurements on mobile devices and is recommended as a result of research, was used, and the A-weighting band was preferred as the measurement type. During the measurement, noise measurement evaluation was conducted in the work carried out by both groups for the airframe patch application (Figures 4 and 5) performed within the scope of practical training.

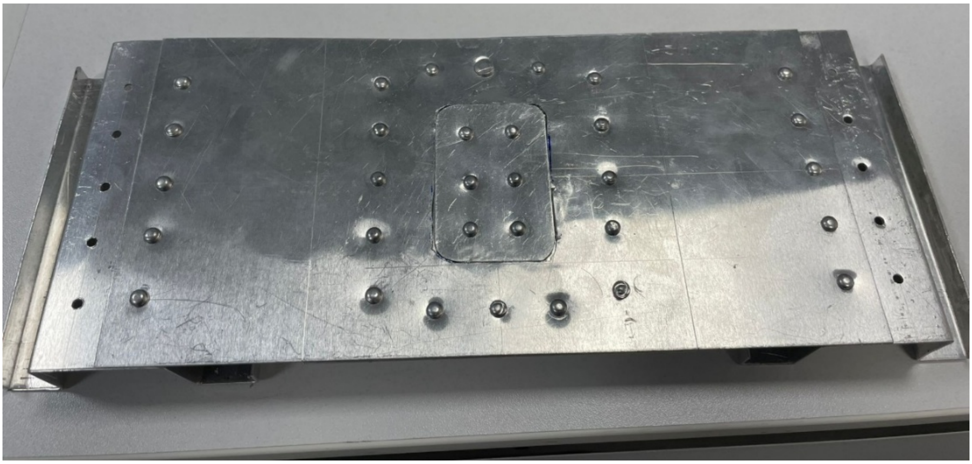

Figure 13. Airframe Patch Application (Front Surface)

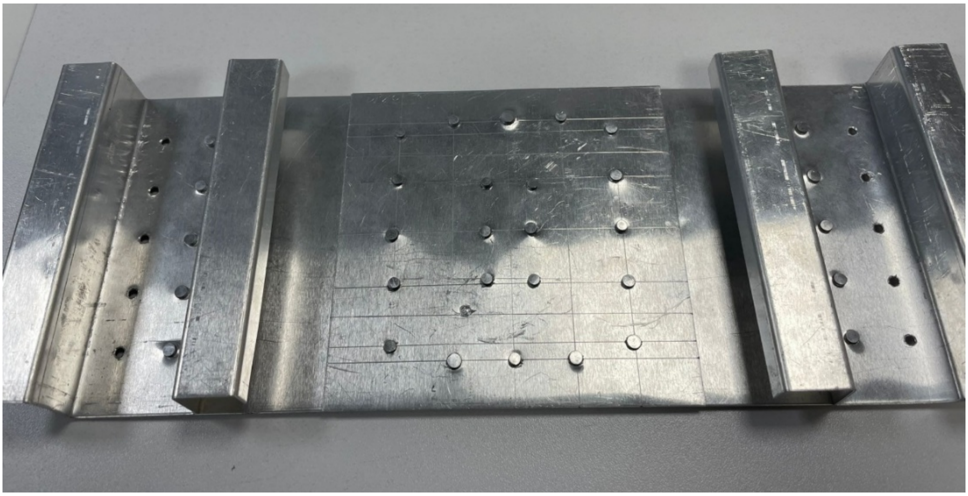

Figure 14. Airframe Patch Application (Back Surface)

According to the data obtained from the results of the first measurement method, in the assessment conducted in the classroom before the riveting gun was used, the student-related ambient noise level in the workshop before starting the part work was recorded over a 10 minute period in the A-weighting band, with a maximum of 83 dBA and an average of 63 dBA.

In the subsequent stage, the recorded noise values were measured in order to evaluate the changes in noise levels depending on the number of riveting guns used. For each tool use, the resulting noise values were measured by increasing the distances sequentially. Considering the noise values obtained, in the measurement with a single riveting gun, when the distance from the source was 1 m, the maximum noise level in the A-weighting band was determined as 114 dBA. In the measurement at a distance of 2 m, 109 dBA was recorded; at 3 m, 107 dBA; and at 4 m, 106 dBA. When the number of riveting guns was increased and the riveting operation was performed simultaneously, it was observed that the maximum noise level was measured as 118 dBA in the A-weighting band at a distance of 1 m, 117 dBA at 2 m, 113 dBA at 3 m, and 110 dBA at 4 m (Figure 6).

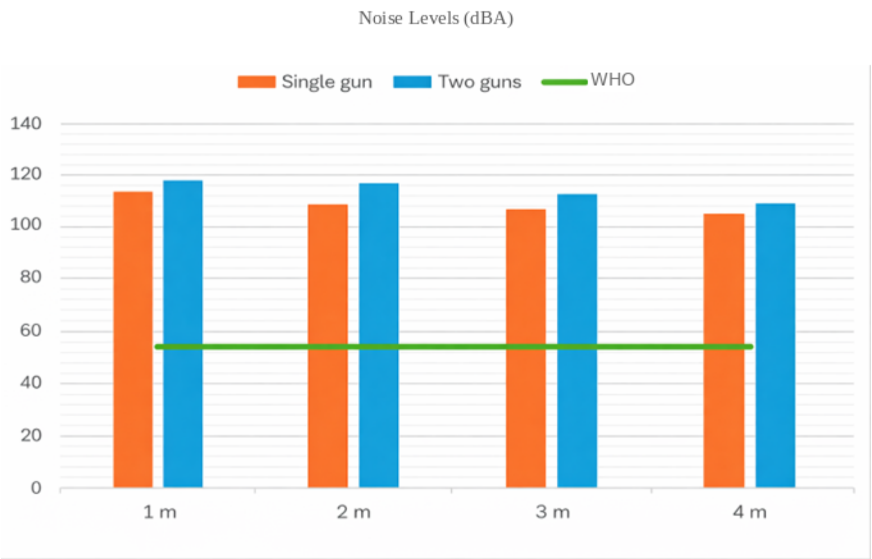

Figure 15.Evaluation of Noise Levels Depending on Distance and Number of Guns According to WHO Limits

CONCLUSION AND RECOMMENDATIONS

When the measurements taken during the riveting operation in the workshop are examined, it is observed that there is an exposure above the specified noise levels. When potential health disorders related to noise level and the measurement results are compared, working for prolonged periods without protection with noisy tools such as riveting creates a risk of stress, sleep disorders, cardiovascular effects, and disorders of the hearing system.

According to the data obtained as a result of the measurement reports, it was observed that the values exceeded the noise limits for Educational

Facility Areas specified within the indoor noise level limit values stated in the Environmental Noise Directive Table.2 (CSB, 2002)

Table 3. Noise Limits in Educational Facility Areas (CSB, 2002)

Area of Use	Leq (dBA)	Time Period
Classrooms in schools, interiors of preschool buildings, laboratories, special education facilities, facilities for persons with disabilities, and similar.	35	During lessons
Gymnasium, cafeteria	55	During the activity period
Preschool bedrooms	30	During sleep

Although the Leq noise values to which students working in workshops are exposed with unprotected ears are specified as 35 dBA during lessons in educational facility areas, the Leq values measured during the conducted activities vary, and a reliable outcome cannot be predicted. The reason for this is that the riveting period does not occur regularly among students, and this leads to variations in the duration of the active riveting gun sound, resulting in different average values. For instance, while the average noise level exposure measured at a distance of 2 m with a single riveting gun was determined as 67 dBA, the average noise level measured at a distance of 3 m was determined as 87 dBA. Therefore, because the riveting period does not progress regularly, the average noise level exposure does not provide reliable data.

An important output of the measurements performed within the scope of this study is that, due to the irregular and impulsive nature of the riveting operation, Leq values alone may be insufficient to represent exposure in every scenario. Therefore, in subsequent studies, directly calculating daily exposure (e.g., based on a working day or lesson duration) may yield more reliable results. In addition, repeating the measurements on different days with similar process scenarios and defining a “standard riveting cycle” will also increase the comparability of the results.

The evaluations indicate that, during practical training activities in workshops, the use of hearing protectors in the operation of equipment that can cause high noise levels, such as pneumatic riveting guns, should be addressed not as a “preference” but as an “obligation.” For this reason, a personal protective equipment practice is recommended that is supported by warning/caution signs at the workshop entrance and in the operation areas and verified with a checklist before the lesson begins. In cases where high peak values may be observed, a "double protection" approach (earplugs + earmuffs) may be considered in addition to a single protector. However, since ensuring correct fitting and sealing is as critical as the presence of the protector, it is recommended that students be provided with a short "proper use training" as a practical session and that periodic checks be carried out by instructors during the term. Establishing a habit of hearing protection in practical training conducted within the scope of SHY-147 will also support a safe working culture in the field after graduation.

Acoustically separating the area where the riveting operation is performed from the workshop environment may be one of the effective approaches to reduce the spread of noise throughout the entire area. For this purpose, the use of portable acoustic barriers/screens or, if possible, the establishment of a semi-enclosed riveting booth is recommended. The use of sound-absorbing materials on ceilings and walls to reduce sound reflections on workshop interior surfaces (especially on large and hard surfaces) may reduce reverberation and, consequently, decrease both perceived noise and communication difficulties.

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