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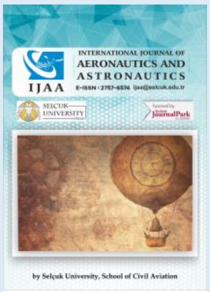

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*Review Article / İnceleme Makalesi*

# Non-destructive testing methods commonly used in aviation / Havacılıkta yaygın olarak kullanılan tahribatsız muayene yöntemleri

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## ABSTRACT

Non-Destructive Testing (NDT) methods play a pivotal role in ensuring the safety and reliability of aircraft in the aviation industry. This article provides a comprehensive overview of the NDT techniques commonly employed in aviation to assess the structural integrity and performance of aircraft components and materials without causing any damage. The article discusses the significance of NDT in aviation, highlighting the importance of early defect detection, maintenance cost reduction, and enhanced operational safety. It delves into various NDT methods, such as ultrasonic testing, eddy current testing, radiographic inspection, magnetic particle testing, and dye penetrant testing, explaining their principles and applications. In addition, in this article, the advantages and disadvantages of NDT methods and which methods are used in which part of the aircraft are mentioned. Understanding these NDT methods is crucial for aviation professionals, as they contribute to the continued airworthiness of aircraft, ensuring that passengers and crew can travel safely and confidently.

## ÖZET

Tahribatsız Muayene (NDT) yöntemleri, havacılık endüstrisinde hava taşıtlarının emniyet ve güvenilirliğinin sağlanmasında çok önemli bir rol oynamaktadır. Bu makale, uçak bileşenlerinin ve malzemelerinin yapısal bütünlüğünü ve performansını herhangi bir hasara yol açmadan değerlendirmek için havacılıkta yaygın olarak kullanılan NDT tekniklerine kapsamlı bir genel bakış sunmaktadır. Makale, erken kusur tespiti, bakım maliyetlerinin azaltılması ve gelişmiş operasyonel güvenliğin önemini vurgulayarak NDT'nin havacılıktaki önemini tartışmaktadır. Ultrasonik test, girdap akımı testi, radyografik muayene, manyetik parçacık testi ve boya penetrant testi gibi çeşitli NDT yöntemlerini inceleyerek bunların ilkelerini ve uygulamalarını açıklamaktadır. Ayrıca bu makalede, NDT yöntemlerinin avantaj ve dezavantajlarından ve hangi yöntemlerin uçağın hangi bölümünde kullanıldığından bahsedilmektedir. Bu NDT yöntemlerini anlamak havacılık profesyonelleri için çok önemlidir, çünkü uçakların uçuşa elverişliliğinin devam etmesine katkıda bulunarak yolcuların ve mürettebatın güvenli ve emin bir şekilde seyahat edebilmelerini sağlarlar.

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## 1. Introduction

The aviation industry stands as a paragon of precision engineering and safety standards. Aircraft, whether for commercial, military, or private use, are complex machines built to exacting specifications. Ensuring their structural integrity, reliability, and safety is of paramount importance. Non-Destructive Testing (NDT) methods are indispensable tools in achieving these goals. NDT methods are the unsung heroes of aviation maintenance and inspection. Unlike traditional destructive testing methods that involve damaging the material or component being examined, NDT techniques enable the evaluation of structural and material integrity without causing harm. These methods are not only integral to the aviation sector but are also applied in various industries, from construction to manufacturing, where safety and quality assurance are paramount. In this article, the aviation-related NDT world will be examined. The importance of NDT in the industry will be explored, highlighting its important role in defect detection, cost reduction and increasing operational safety. Additionally, NDT methods commonly used in aviation will be examined in depth, including dye penetrant testing, magnetic particle testing, eddy current testing, ultrasonic testing, and radiographic inspection. By understanding the principles and applications of these techniques, aviation professionals can make informed decisions, ensuring the airworthiness of aircraft and the safety of passengers and crew [1-3].

### 2. Common NDT Methods in Aviation

#### 2.1. Dye penetrant testing

Dye Penetrant Testing (DPT), also known as Liquid Penetrant Testing (LPT) or simply Penetrant Testing, is a widely used Non-Destructive Testing (NDT) method in aviation and various other industries. This technique is employed to detect surface-gap defects or discontinuities in aircraft components and materials without causing any damage to them (Fig. 1). The primary purpose of dye penetrant testing in aviation is to ensure the structural integrity, safety, and airworthiness of critical aircraft parts [4].

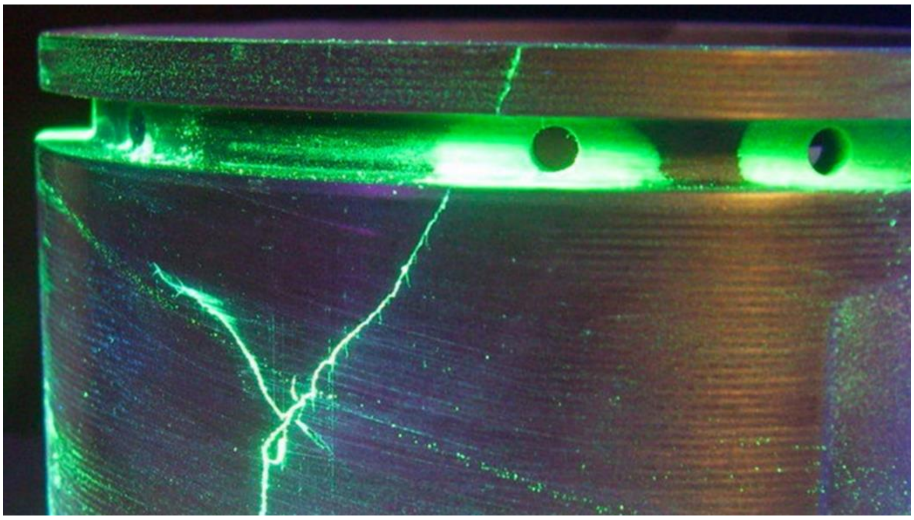

**Fig. 1.** Fluorescence penetrant testing [5]

Here's how the process typically works (Fig. 2): Surface Preparation: Before the testing begins, the surface of the aircraft component under examination is cleaned to remove any contaminants, such as dirt, oil, or corrosion. This step is crucial to ensure the accuracy of the test.
Application of Penetrant: A brightly colored, highly visible liquid penetrant is applied to the surface of the component. This penetrant is chosen based on the specific requirements of the test.


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Dwell Time: The penetrant is left on the surface for a specified period, allowing it to seep into any surface-breaking defects, cracks, or discontinuities.
Excess Penetrant Removal: After the dwell time, any excess penetrant is carefully removed from the surface. This is typically done by wiping or rinsing.
Application of Developer: A white, powdery developer is applied to the surface. The developer draws the penetrant out of any defects, making them visible.
Visual Inspection: The inspector then examines the surface for any indications or indications - these are the visible signs of defects, revealed by the penetrant's presence. These indications can be cracks, porosity, or other surface irregularities.

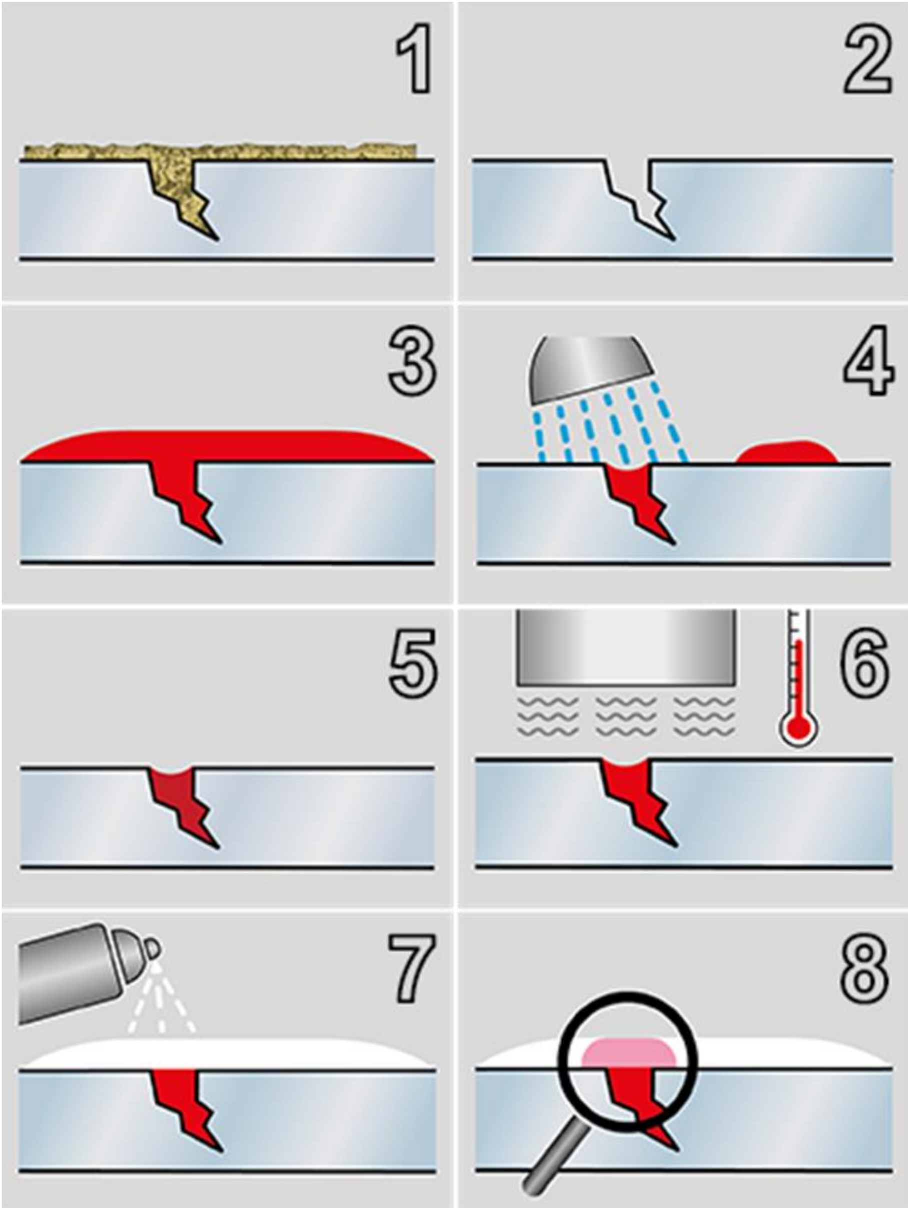


**Fig. 2**. Principles of dye penetrant testing [6]


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Interpretation and Evaluation: The inspector interprets the indications based on their size, shape, and location to determine the nature and significance of the defects. This evaluation is crucial in determining whether the component is suitable for continued use or requires repair or replacement.

Dye penetrant testing is especially valuable for detecting defects in materials that are not easily visible to the naked eye. It is a highly sensitive and cost-effective method for ensuring the safety and airworthiness of aircraft components. Regular inspections using this technique help maintain the structural integrity of aircraft and contribute to the overall safety of aviation operations [7, 8].

### 2.1.1. Advantages of dye penetrant testing

Sensitivity: DPT is highly sensitive and capable of detecting very small surface-breaking defects, including cracks, pores, and other discontinuities that may not be visible to the naked eye. This makes it an effective method for identifying hidden flaws in aircraft components.

Versatility: DPT can be used on a wide range of materials, including metals, plastics, ceramics, and composites, making it a versatile choice for the aviation industry, where various materials are used in aircraft construction.

Cost-Effective: DPT is relatively cost-effective compared to other NDT methods, making it an attractive option for routine inspections and maintenance. It doesn't require complex or expensive equipment.

Ease of Application: The method is straightforward and can be applied with minimal training. Technicians can quickly learn how to perform DPT effectively.

No Damage to the Component: As a non-destructive testing method, DPT does not damage the tested components, allowing them to remain in service if they pass inspection [9].

### 2.1.2. Disadvantages of dye penetrant testing

Surface Dependency: DPT is limited to detecting surface-breaking defects. It cannot identify subsurface or internal flaws in materials. If a defect is located beneath the surface, DPT will not detect it.

Time-Consuming: Dye penetrant testing is a time-consuming process, typically involving several steps (application, dwell time, removal, and developer application) and often requiring multiple applications for thorough inspection.

Environmental Concerns: The process involves the use of chemicals, which can raise environmental and health concerns if not handled and disposed of properly. Some of the chemicals used in DPT may be hazardous.

Operator Skill: While it is relatively easy to learn, the effectiveness of DPT depends on the skill and experience of the technician performing the test. Inexperienced or poorly trained technicians may miss defects or misinterpret results.

Limited to Surface Inspection: DPT is limited to surface inspection, and it may not provide a comprehensive assessment of the overall condition of a component. Other NDT methods, such as radiographic or ultrasonic testing, may be necessary to complement DPT for a more thorough evaluation.

In conclusion, dye penetrant testing is a valuable tool for detecting surface defects in aviation components, but it has limitations, and its effectiveness depends on various factors. In practice, it is often used in combination with other NDT methods to ensure a comprehensive evaluation of aircraft components [10].

### 2.1.3. Common applications of DPT in aviation

DPT is used to inspect the surfaces of various structural components of an aircraft, such as the fuselage, wings, tail, and landing gear. It helps identify surface cracks, defects, and imperfections that may compromise the structural integrity of these components [11].


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### 2.2. Magnetic testing

Magnetic particle testing (MPT), also known as magnetic testing or magnetic particle inspection (MPI), is a non-destructive testing (NDT) method commonly used in aviation and other industries to identify surface and near-surface defects in ferromagnetic materials (Fig. 3).

**Fig. 3.** Magnetic testing [12]

Ferromagnetic materials are those that can be magnetized, such as iron and steel. Magnetic testing relies on the principle that when a magnetic field is applied to a ferromagnetic material, it will exhibit unique magnetic properties when defects are present.

The process of Magnetic Particle Testing in Aviation:

Preparation: The first step involves the careful cleaning and preparation of the component or material to be inspected.

Magnetization: The component is magnetized by applying a magnetic field. This can be done using a yoke (a handheld magnetizing device) or by passing an electric current through the material.

Application of Magnetic Particles: After magnetization, finely divided magnetic particles (often iron or iron oxide) are applied to the surface of the component. These particles are typically in the form of a dry powder or a wet suspension, which is sprayed or brushed onto the surface.

Inspection: As the magnetic particles are applied to the surface, they will be attracted to and accumulate at areas where there are magnetic field disturbances, such as those caused by surface cracks, weld defects, or other discontinuities. These areas will appear as a distinct pattern of accumulations on the surface, indicating the presence of defects.

Interpretation: A trained inspector examines the accumulated magnetic particles to identify the location, size, and shape of any defects. The pattern of magnetic particle accumulations provides visual evidence of the defects [13,14].

#### 2.2.1. Advantages of magnetic testing

Effective for detecting surface and near-surface defects. Quick and relatively simple process. Can be used on a wide range of ferromagnetic materials. Immediate visual results. Non-destructive, meaning it doesn't harm the tested components [15].



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### 2.2.2. Disadvantages of magnetic testing

Limited to ferromagnetic materials (not applicable to non-magnetic materials). Limited to surface and near-surface defects. Requires proper surface preparation for accurate results. The process may be limited in inspecting complex geometries or areas with restricted access [16].

### 2.2.3. Common applications of magnetic testing in aviation

Aircraft Engine Components: MPT is widely used to inspect critical engine components, such as turbine blades, compressor disks, and engine casings (Fig. 4).
Landing Gear Components: Landing gear components, including landing gear struts, axles, and associated parts, are subject to significant stress during takeoffs and landings (Fig. 5).

**Fig. 4.** Magnetic testing of engine components [17]

**Fig. 5.** Magnetic testing of landing gear components [18]

Structural Components: MPT is applied to various structural components of the aircraft, including the fuselage, wings, and tail sections and bolts, fasteners, and rivets: Aircraft rely on numerous bolts, fasteners, and rivets to hold components together [19].

### 2.3. Eddy current testing

Eddy current testing (ECT) is a non-destructive testing (NDT) method used in aviation to evaluate the structural integrity and detect surface defects in aircraft components, particularly those made from conductive materials like aluminum and some types of alloys (Fig. 6).

**Fig. 6.** Eddy current testing of landing gear [20]

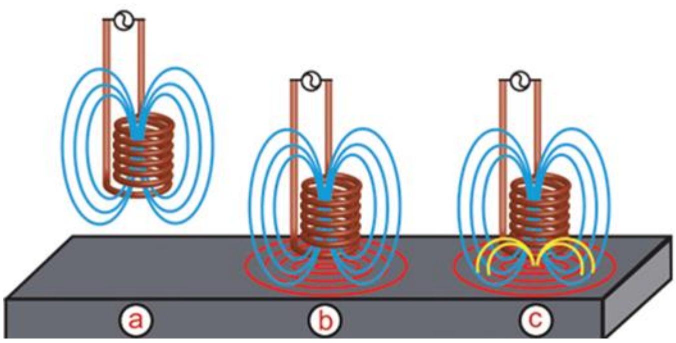


**Fig. 7.** Basic principles of ECT [22]


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Eddy current testing is based on the principle of electromagnetic induction. When an alternating current is passed through a coil or probe, it generates a fluctuating magnetic field. When this coil or probe is placed near a conductive material, the changing magnetic field induces eddy currents—circular electrical currents—within the material. The interaction between these eddy currents and the material's conductivity creates a secondary magnetic field. When the material has defects, such as cracks, voids, or corrosion, the eddy currents are disrupted, resulting in changes in the secondary magnetic field.

The process of eddy current testing in aviation (Fig. 7):

Probe or coil setup: A coil or probe is placed in close proximity to the surface of the material to be inspected. The coil or probe is connected to an eddy current testing instrument.

Excitation: An alternating current is passed through the coil or probe, generating a fluctuating magnetic field.

Eddy current generation: Eddy currents are induced in the conductive material being tested due to the changing magnetic field [19,21].

Detection and analysis: As the eddy currents interact with the material's properties, changes in the secondary magnetic field occur. The instrument detects these changes, and the data is displayed for analysis [23].

#### 2.3.1. Advantages of eddy current testing

Eddy current testing is a relatively quick inspection method. Unlike some other NDT methods, ECT does not typically require extensive surface preparation. This can save time and resources, particularly when inspecting large aircraft structures. ECT is a non-destructive testing method, meaning it does not harm the material being inspected. This is crucial in aviation, where the integrity of components must be maintained. ECT is versatile and can be used on a variety of conductive materials, including aluminum, steel, titanium, and certain alloys, making it suitable for different aircraft components. ECT can be performed on irregularly shaped or difficult-to-reach areas, making it suitable for inspecting complex aerospace components. ECT is well-suited for high-volume manufacturing processes, ensuring the quality and safety of aircraft components [24].

#### 2.3.2. Disadvantages of eddy current testing

ECT is primarily effective on conductive materials, such as metals. It is not suitable for inspecting non-conductive materials like plastics or composites. ECT is generally limited to detecting defects close to the surface. It may not effectively identify defects located deep within thick materials. External electromagnetic interference or variations in material properties can affect the accuracy of ECT results. It is essential to control external factors to obtain reliable results. ECT equipment can be relatively expensive to purchase, maintain, and calibrate. This can be a barrier to some smaller aviation maintenance facilities [25].

#### 2.3.3. Common applications of eddy current testing in aviation

ECT is used to inspect the skin of aircraft, including the fuselage and wings, for surface cracks, corrosion, and other defects. ECT is employed to inspect fasteners like bolts, rivets, and screws for cracks, corrosion, and material degradation. Aircraft engines are subject to high stress and temperature conditions. ECT is used to examine engine components, such as turbine blades, for defects that may affect engine performance and safety. ECT helps evaluate the landing gear components, such as landing gear struts, axles, and connecting parts, for defects that could lead to landing gear failure during takeoffs and landings. In modern aviation, composite materials are used extensively. ECT is applied to detect hidden flaws, delamination, or voids within composite materials to ensure their structural integrity [26].

### 2.4. Ultrasonic testing

Ultrasonic testing relies on the principle of sending high-frequency sound waves (ultrasound) into a material and measuring the time it takes for the sound waves to reflect back. The system uses a transducer that emits ultrasound


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waves and receives the returning signals (Fig. 8). These sound waves propagate through the material, and when they encounter a change in material properties, such as a void, crack, or other discontinuity, some of the waves are reflected back to the transducer. The reflected waves are analyzed to determine the size, location, and nature of any defects.

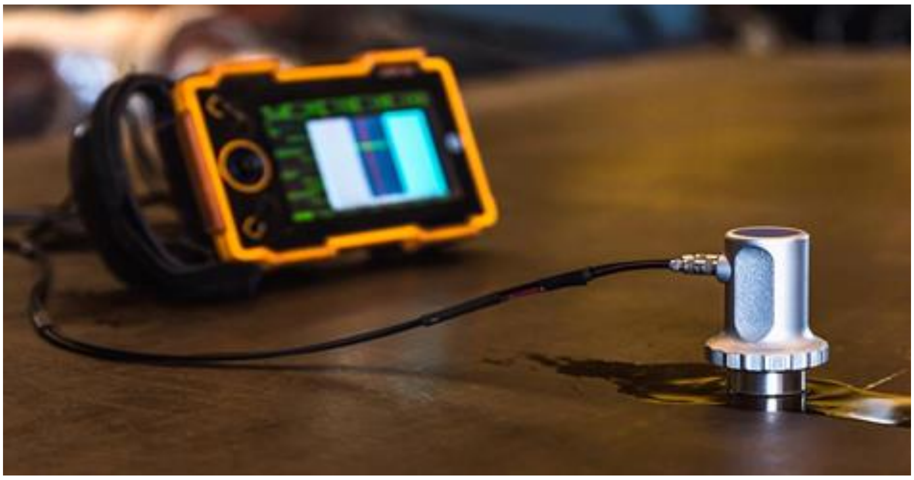

**Fig. 8.** Ultrasonic testing system

Here's how the process typically works:
Preparation: The first step is to prepare the surface of the material or component to be inspected. This usually involves cleaning the surface to remove any contaminants, such as grease, oil, dirt, or corrosion. Proper surface preparation is essential to ensure accurate results.
Transducer Setup: A transducer is a key component of the UT equipment. The transducer is a handheld device that generates and receives ultrasonic waves. A couplant, typically a gel or a special coupling fluid, is applied to the surface of the material to help transmit the ultrasonic waves.
Generation of Ultrasonic Waves: The transducer is placed on the surface of the material, and it generates high-frequency sound waves, typically in the range of 0.5 to 25 megahertz (MHz). These sound waves are introduced into the material and travel through it.
Propagation of Sound Waves: The ultrasonic waves propagate through the material. As they travel through the material, they encounter boundaries, interfaces, and any internal defects or anomalies within the material.
Reflection of Sound Waves: When the ultrasonic waves encounter a change in the material, such as the back surface, an internal defect, or a void, a portion of the waves is reflected back towards the transducer. The time it takes for the reflected waves to return is recorded and used to determine the distance to the reflecting interface.
Display and Analysis: The data collected from the ultrasonic waves is displayed on a screen or monitor. A skilled technician or inspector can interpret the results by analyzing the ultrasonic waveform and the time it takes for the waves to travel. The presence and characteristics of any defects, such as cracks or voids, can be identified [28, 29].

### 2.4.1. Advantages of ultrasonic testing

High sensitivity to both surface and subsurface defects.
Versatility in inspecting a wide range of materials, including metals, composites, and plastics. The ability to provide quantitative data about defect size and depth. Real-time inspection, allowing for immediate assessment of component integrity. Non-destructive nature, which means it does not harm the tested components.


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### 2.4.2. Disadvantages of ultrasonic testing

Requires well-trained and certified technicians for accurate results. In some cases, it may be necessary to access both sides of the material being tested, which can be challenging in some aircraft components. Surface finish and complex geometry can affect the accuracy of the inspection [30].

### 2.4.3. Common applications of ultrasonic testing in aviation

Ultrasonic testing is used to inspect the integrity of critical structural components, such as the aircraft's fuselage, wings, tail, and landing gear [30].

## 2.5. Radiographic inspection

Radiographic inspection testing relies on the principle that X-rays or gamma rays can penetrate through materials to varying degrees, depending on the material's thickness, density, and composition (Fig. 9). When these rays pass through the material, they are absorbed or scattered by the internal structure of the material, creating a shadow image on a radiographic film or digital detector. Areas with different densities, such as defects or anomalies, appear as variations in the shadow image.

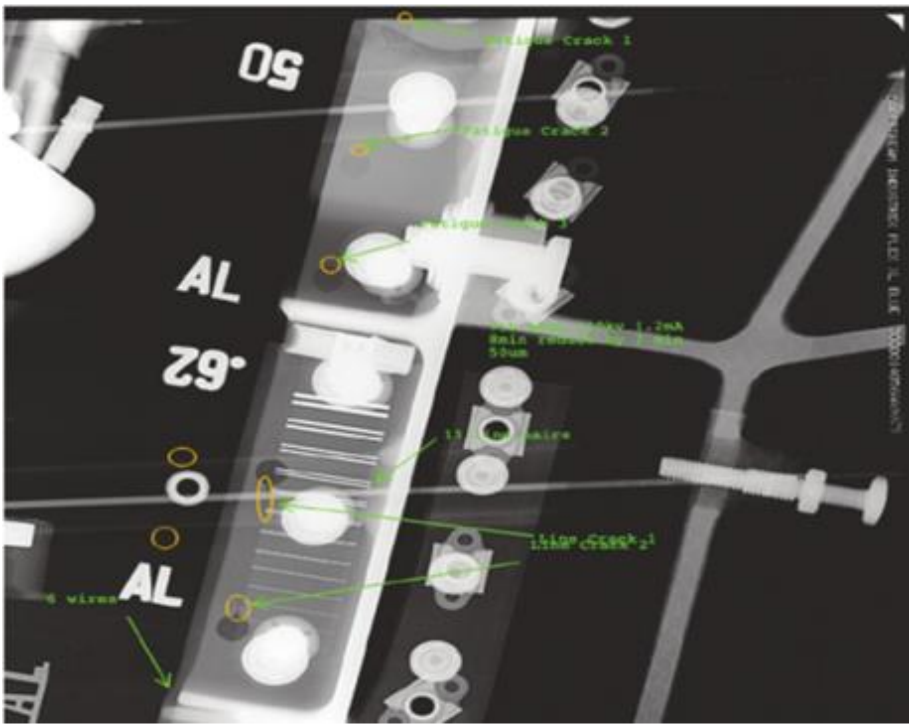


**Fig. 9.** Radiograph of typical aircraft wing spar [31]

The process of radiographic inspection testing in aviation:
A radiation source is used to produce X-rays or gamma rays. X-ray machines generate X-rays through the interaction of high-energy electrons with a metal target, while gamma-ray sources emit gamma rays from radioactive isotopes like iridium-192 or cobalt-60. The radiation source is directed at the material or component being inspected (Fig. 10). The X-rays or gamma rays penetrate the material and create a latent image on a radiographic film or digital detector. The exposed radiographic film or digital detector records the radiation that passes through the material. The film may need to be developed, while digital detectors provide immediate results. A trained radiographic technician or inspector examines the radiographic image to identify the location, size, and characteristics of any defects, such as cracks, voids, or inclusions [32].



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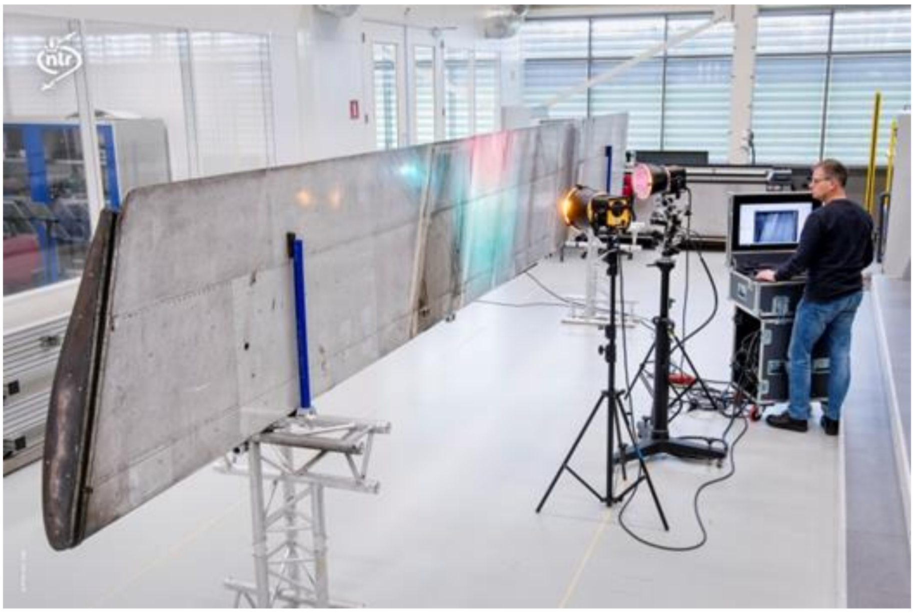

**Fig. 10.** Radiation source for radiographic testing [33]

### 2.5.1. Advantages of radiographic inspection

Radiographic testing is suitable for a wide range of materials, including metals, composites, and some non-metallic materials. This versatility allows it to be used on various aircraft components. Radiography can provide a full internal view of the test material, offering comprehensive coverage. Radiographic testing is highly sensitive to a wide range of defects, making it an effective method for detecting small or subtle irregularities within the material. Digital radiography systems offer real-time imaging, allowing for immediate examination of the results. This can expedite the inspection process and decision-making. Radiographic images provide quantitative data that can be used to measure the size and depth of defects, aiding in defect characterization and evaluation. Radiography is particularly effective for identifying defects hidden within the material, which might otherwise remain unnoticed and lead to catastrophic failures [34].

### 2.5.2. Disadvantages of radiographic inspection

Radiographic inspection, despite its many advantages, also has several disadvantages and limitations when used in aviation for non-destructive testing (NDT). These disadvantages should be taken into consideration. One of the most significant drawbacks of radiographic inspection is the exposure to ionizing radiation. This poses health and safety risks to personnel who operate the equipment. The use of ionizing radiation sources in aviation necessitates strict compliance with regulatory requirements. This includes proper certification, licensing, and adherence to radiation safety guidelines, which can be time-consuming and costly. Radiographic inspection equipment, especially high-quality and portable systems, can be expensive to acquire and maintain. This can be a barrier to smaller aviation maintenance facilities. The disposal of radioactive materials or radioactive waste generated during radiographic inspections must be managed carefully to minimize environmental impact. The quality of radiographic images can be influenced by factors such as radiation source, geometry, and material density. Factors like scattered radiation can reduce image quality and make interpretation challenging. Radiography may be sensitive to variations in temperature and humidity, which can affect the quality of the radiographic image.

While radiographic inspection is a valuable NDT method for aviation, these disadvantages underscore the need for careful planning, proper training, strict adherence to safety protocols, and the consideration of alternative NDT methods in situations where radiography may not be practical or safe [35].


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## 3. Conclusion

In conclusion, non-destructive testing (NDT) methods are indispensable tools in the aviation industry, serving as the backbone of safety, reliability, and airworthiness. Throughout this article, we have explored several NDT methods commonly used in aviation, each offering its unique set of advantages and limitations. The advantages of these NDT methods include their non-destructive nature, high sensitivity, and the ability to detect defects at various depths, making them vital in ensuring the structural integrity of aircraft components. In the aviation industry, where safety is paramount, a combination of these NDT methods is often used in tandem to ensure the reliability and airworthiness of aircraft. This multi-pronged approach allows for thorough inspections, early defect detection, and informed decision-making during maintenance and repairs.

***Authorship contribution statement for Contributor Roles Taxonomy***

**Özlem Ulus,** *Writing - original draft, Investigation, Visualization*. **Furkan Eren Davarcı,** *Investigation, Writing*. **Elif Eren Gültekin,** *Visualization and Formal Analysis.*

**Conflicts of Interest:** The authors declare no conflict of interest.

## References

[1] Çınar, Z.M., Nuhu, A.A., Zeeshan, Q., Korhan, O., Asmael, M. and Safaei, B. 2020. Machine learning in predictive maintenance towards sustainable smart manufacturing in industry 4.0. Sustainability, 12(19), 8211.
[2] Dinis, D. and Barbosa-Póvoa, A.P. On the optimization of aircraft maintenance management, in: Póvoa, A., de Miranda, J., Operations Research and Big Data, 15, Springer International Publishing, Switzerland, 2015, 49-57.
[3] Regattieri, A., Gamberi, M., Gamberini, R. and Manzini, R. 2005. Managing lumpy demand for aircraft spare parts. Journal of Air Transport Management, 11(6), 426-431.
[4] Kryukov, I.I., Leont'ev, S.A., Platonov, V.S. and Rybnikov, A.I. 2008. Testing of discs of turbine rotors of gas compressors with the dye penetrant nondestructive testing technique. Russian Journal of Nondestructive Testing, 44(8), 542-547.
[5] Florescent penetrant inspection (FPI). https://www.norwoodmedical.com/capabilities/florescent-penetrant-inspection-fpi (June 25, 2024).
[6] Basic knowledge about dye penetrant testing. https://www.karldeutsch.de/ndt-knowledge/basic-knowledge/basic-knowledge-about-penetration-or-dye-penetrant-testing/?lang=en (June 15, 2024).
[7] Adair, T.L. and Kindrew, M.G. 2000. Automated fluorescent penetrant inspection (FPI) system is triple A. 15th World Conference on Nondestructive Testing, 15-21 October, Rome, Italy.
[8] Schmidt, R.A., Fracture-toughness testing of limestone: KIc of indiana limestone was measured using three-point-bend specimens, and toughness is seen to increase with crack length much like many aluminum alloys. Experimental mechanics, 1976. 16(5): p. 161-167.
[9] Kryukov, I.I., Leont'ev, S.A., Platonov, V.S. and Rybnikov, A.I. 2006. The experience of application of dye penetrant nondestructive testing in diagnostics of gas turbines. Gas Turbine Technologies, 7, 10-12.
[10] Swartz, S.E., Hu, K.K. and Jones, G.L. 1982. Techniques to monitor crack growth in plain concrete beams. Experimental Techniques, 6(6), 2-4.


https://doi.org/10.55212/ijaa.1418742

[11] Swartz, S.E. 1982. Stress-intensity factor for plain concrete in bending—Prenotched versus precracked beams. Experimental Mechanics, 22(11), 412-417.
[12] QUALITEST: Quality testing & inspection services ltd. https://qualitytestingtt.com/ (25.06.2024).
[13] Velazco, G., Visalvanich, K. and Shah, S.P. 1980. Fracture behavior and analysis of fiber reinforced concrete beams. Cement and Concrete Research, 10(1), 41-51.
[14] Wecharatana, M. and Shah, S.P. 1982. Slow crack growth in cement composites. Journal of the Structural Division, 108(6), 1400-1413.
[15] Qiu, Z., Zhang, W., Yu, X., Guo, Y. and Jin, J. 2015. Monitoring yield failure of ferromagnetic materials with spontaneous abnormal magnetic signals. Tehnički vjesnik, 22(4), 953-958.
[16] Zhong, L., Li, L. and Chen, X. 2012. Simulation of magnetic field abnormalities caused by stress concentrations. IEEE Transactions on Magnetics, 49(3), 1128-1134.
[17] Li, Z., Dixon, S., Cawley, P., Jarvis, R. and Nagy, P.B. 2017. Study of metal magnetic memory (MMM) technique using permanently installed magnetic sensor arrays. 43rd Annual Review of Progress in Quantitative Nondestructive Evaluation, 36, 110011-1–110011-8.
[18] Aviation NDT inspections. https://atslab.com/nondestructive-testing/aviation-ndt-inspections/ (October 11, 2020).
[19] Guo, P.J., Chen, X.D., Guan, W.H. and Zhao, H.J. 2015. Correlation between magnetic memory signals and mechanical properties of 35CrMo tempered and quenched steel. Applied Mechanics and Materials, 750, 186-191.
[20] Eddy current testing of aircraft. https://www.ndt.com.ua/en/applications/aircraft-testing/eddy-current-testing-of-aircraft (May 14, 2023).
[21] Noorian, F. and Sadr, A. 2010. Computation of transient eddy currents in EMATs using discrete Picard Method. 18th Iranian Conference on Electrical Engineering, 11-13 May, Isfahan, Iran.
[22] Overview of eddy current testing (ECT). https://inspectioneering.com/tag/eddy+current (May 14, 2023).
[23] Staszewski, W.J. Structural health monitoring using guided ultrasonic waves, in: Holnicki-Szulc, J., Soares, C.M., Advances in Smart Technologies in Structural Engineering, Springer, Berlin, Heidelberg, 2004, 117-162.
[24] Janousek, L., Capova, K., Yusa, N. and Miya, K. 2008. Multiprobe inspection for enhancing sizing ability in eddy current nondestructive testing. IEEE Transactions on Magnetics, 44(6), 1618-1621.
[25] Metcalfe, G. 1990. The use of electrical conductivity measurements in detecting heat and fire damage in aircraft structure. IEE Colloquium on NDT Technology in Aerospace, 15 January, London, UK, 2/1-2/4.
[26] Rojek, M., Stabik, J. and Wróbel, G. 2005. Ultrasonic methods in diagnostics of epoxy–glass composites. Journal of Materials Processing Technology, 162-163, 121-126.
[27] What are Advantages and Limitations of Ultrasonic Testing? https://www.europeanbusinessreview.com/what-are-advantages-and-limitations-of-ultrasonic-testing/ (May 14, 2023).
[28] Martínez-Soto, F., Ávila, F., Puertas, E. and Gallego R. 2023. FFRC and SASW nondestructive evaluation of concrete strength from early ages. Journal of Building Engineering, 76, 107093.
[29] Abbass, W. Aslam, F., Ahmed, M., Ahmed, A., Alyousef, R. and Mohamed, A. 2023. Predicting the performance of existing pre-cast concrete pipes using destructive and non-destructive testing techniques. Heliyon, 9(5), e15471.
[30] Sari, M., Yilmaz, E., Kasap, T. and Karacasu, S. 2023. Exploring the link between ultrasonic and strength behavior of cementitious mine backfill by considering pore structure. Construction and Building Materials, 370, 130588.


https://doi.org/10.55212/ijaa.1418742

[31] Wong, B.S., Wang, X., Koh, C.M., Tui, C.G., Tan, C.S. and Xu, J. 2011. Crack detection using image processing techniques forradiographic inspection of aircraft wing spar. Insight: Non-Destructive Testing and Condition Monitoring, 53(10), 552-556.

[32] Allen, J.C.P. and Ng, C.T. 2023. Damage detection in composite laminates using nonlinear guided wave mixing. Composite Structures, 311, 116805.

[33] Composite testing. https://jaxalabs.com/composite-testing/ (26.06.2024).

[34] Shelkovenko, T., Sinars, D.B., Pikuz, S.A., Chandler, K.M. and Hammer, D.A. 2001. Point-projection x-ray radiography using an X pinch as the radiation source. Review of Scientific Instruments, 72(1), 667-670.

[35] Dey, A.K., Radiographic testing: Principles, procedures, standards, and advantages and disadvantages. https://whatispiping.com/radiographic-testing/ (25.06.2024).



https://doi.org/10.55212/ijaa.1418742