International Journal of Mechanical and Sustainability Engineering Technology

Journal homepage:
https://uniexpertsacademy.com/index.php/IJMSET/index
ISSN: **3083-8363**

Frequency Optimization of Eddy Current Testing for Surface Flaw Detection in Aluminum and Stainless-Steel Aerospace Components

Arthur William Velu[1], Mohamad Nur Hidayat Mat[2], Muhammad Shukri Sa'don[3], Tawhidul Islam Khan[4], Eliza M. Yusup[1,*]

[1] Faculty of Mechanical and Manufacturing Engineering, Universiti Tun Hussein Onn Malaysia (UTHM), 86400 Parit Raja, Johor, MALAYSIA

[2] Faculty of Mechanical and Automotive Engineering, Universiti Malaysia Pahang Al-Sultan Abdullah, 26600 Pekan, Pahang, MALAYSIA

[3] Proceanic Engineering Malaysia Sdn Bhd., No.36, Jalan Teras 3, Senibong 88, Kawasan Perindustrian Kota Puteri,81750 Masai, Johor, MALAYSIA

[4] Biomedical Engineering, Department of Advanced Health Sciences, Saga University, 1 Honjo-machi, Saga 840-8502, JAPAN.

ARTICLE INFO

Article history:
Received 17 August 2024
Received in revised form 30 June 2026
Accepted 30 June 2026
Available online 09 July 2026

Keywords:

Eddy current testing; non-destructive testing; aerospace components; surface flaw detection; frequency optimization; aluminium; stainless steel

ABSTRACT

Fatigue cracks, corrosion, and surface discontinuities in aircraft components can reduce structural integrity and increase the risk of in-service failure. Reliable non-destructive testing is therefore essential for rapid aircraft maintenance without damaging components. This study evaluates the frequency response of Eddy Current Testing (ECT) for surface flaw detection in aluminium and stainless-steel aerospace components. The inspection was conducted using an Olympus Nortec 600 with a right-angle flexible metal shaft surface probe. Aluminium and stainless-steel calibration blocks were used as reference standards before testing selected Learjet 24D components, namely the wheel hub and landing gear. Five excitation frequencies, 100, 200, 300, 400, and 500 kHz, were investigated to determine the most stable, distinguishable, and repeatable signal response for each material. Measurements were recorded over five consecutive days to improve consistency and minimize variation due to probe handling or testing conditions. The results show that ECT response is strongly influenced by material properties and excitation frequency. For the aluminium wheel hub, 100–300 kHz produced weaker and less distinct waveforms, whereas 400 kHz generated the most stable and clearly defined signal. However, 500 kHz became less stable, indicating reduced signal reliability for the tested aluminium component. For the stainless-steel landing gear, lower frequencies produced limited waveform responses, but signal clarity improved with increasing frequency. The most distinguishable response was obtained at 500 kHz, suggesting better surface sensitivity for stainless steel. Based on waveform stability and signal clarity, 400 kHz is recommended for aluminium components, while 500 kHz is recommended for stainless-steel components. Further work should quantify defect depth, lift-off effect, coating influence,

* *Corresponding author.*
E-mail address: elizay@uthm.edu.my

and probability of detection using controlled artificial flaws and larger samples.

1. Introduction

Fatigue cracks, corrosion, and surface discontinuities in aircraft components can lead to serious structural problems and compromise flight safety if undetected at an early stage. These defects may occur under different aircraft operating conditions and are commonly associated with cyclic loading, environmental exposure, material degradation, and stress concentrations at critical locations such as fastener holes, joints, wheels, hubs, and landing gear components. Therefore, reliable inspection methods are required to detect potential defects without damaging the inspected component. Non-destructive testing (NDT) methods are widely used in the aviation industry to evaluate the condition of aircraft structures, identify defects, and support preventive maintenance activities [1].

Several NDT techniques are commonly applied in aircraft inspection, including Ultrasonic Testing (UT), Radiographic Testing (RT), Magnetic Particle Testing (MPT), Dye Penetrant Testing (DPT), Eddy Current Testing (ECT), and Visual Inspection. Each method has specific advantages and limitations depending on the material type, defect location, inspection depth, surface condition, and the component's accessibility. UT is suitable for detecting internal defects using high-frequency sound waves, but it usually requires surface coupling and skilled interpretation. RT is effective for identifying internal discontinuities such as voids, inclusions, and cracks, but it involves radiation safety concerns and requires controlled inspection conditions. MPT is sensitive to detecting surface and near-surface defects, but it is limited to ferromagnetic materials. DPT is simple and useful for detecting surface-breaking defects in non-porous materials, but it requires cleaning, surface preparation, and direct access to the defect opening. Visual inspection is fast and inexpensive, but it is limited to visible defects and depends strongly on the inspector's experience.

Compared with these methods, Eddy Current Testing offers several advantages for aircraft maintenance because it is rapid, sensitive to surface and near-surface flaws, and requires minimal surface preparation. ECT is particularly suitable for conductive materials such as aluminum and stainless steel, which are commonly used in aircraft structures. It can also be used to inspect critical areas, including rivet and fastener holes, wheel hubs, landing gear components, airframe structures, and other metallic aircraft parts. However, ECT also has limitations. Its effectiveness depends on probe frequency, electrical conductivity, magnetic permeability, lift-off, coating thickness, component geometry, and the orientation of the flaw. In addition, its depth of penetration is limited, especially at higher frequencies, which makes the detection of deeper subsurface flaws more challenging.

1.1 Eddy Current Testing (ECT)

Eddy Current Testing is widely used in the aerospace industry, particularly for detecting service-induced cracks caused by fatigue, corrosion, or stress concentration. Eddy Current Inspection requires minimal surface preparation and provides high sensitivity for surface and near-surface defects. This method is especially valuable for inspecting cracks around aluminum fastener holes, where fatigue crack initiation and propagation can significantly reduce the structural integrity of aircraft components [2].

ECT operates based on electromagnetic induction. When an alternating current flows through a probe coil, it generates an alternating magnetic field. When the probe is placed near a conductive material, the magnetic field induces circulating electrical currents known as eddy currents within the material. Any discontinuity, such as a crack, corrosion pit, material thinning, or change in material properties, disturbs the flow of eddy currents. This disturbance changes the impedance of the probe coil or the detected magnetic field, allowing the defect or material variation to be identified [3,4]. Figure 1 illustrates the basic working principle of ECT.

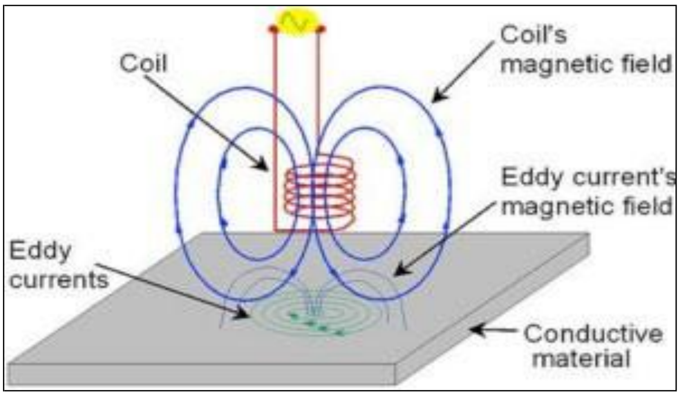


Fig. 1. The working principle in Eddy Current Testing [4]

The basic principle of conventional ECT and eddy current array technology is similar. Both methods rely on the interaction between an induced electromagnetic field and the conductive test material. When a defect interrupts the natural flow of eddy currents, the probe detects a change in signal response. This signal can then be interpreted to identify surface or near-surface defects, measure material thickness, or assess local variations in conductivity and permeability. Figure 2 illustrates the principle of the ECT method: the probe induces eddy currents in the test component and detects changes caused by discontinuities.

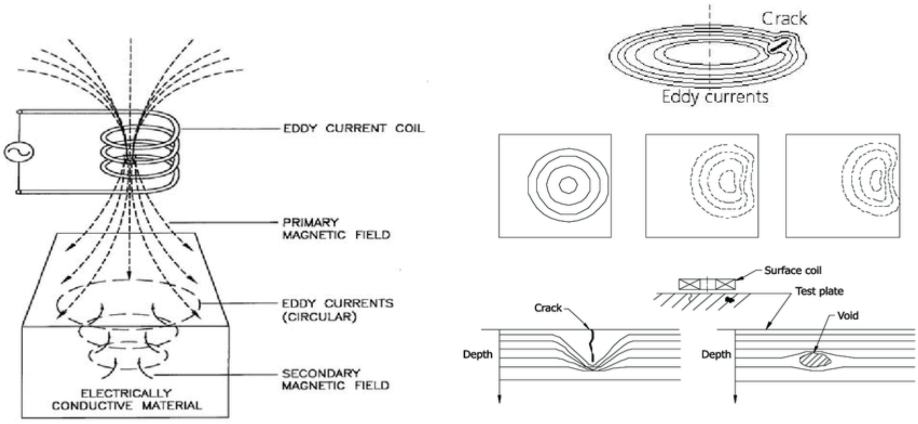


Fig. 2. Principle of Eddy Current Testing Method

In aircraft structures, ECT has been used to inspect riveted joints, multi-layered skins, fastener holes, and other metallic components. Previous studies have shown that cracks may initiate from fastener holes and propagate along aircraft skin structures, especially in regions subjected to repeated loading. Eddy current methods are also effective for identifying corrosion in multi-layered aircraft skins and other critical structural areas [5]. Figure 3 shows the common applications of low- and high-frequency ECT, while Figure 4 presents an example of riveted-joint inspection using ECT-based imaging.

The selection of frequency is one of the most important factors in ECT inspection. Higher frequencies generally provide better sensitivity to surface defects because the eddy currents are concentrated closer to the material surface. However, higher frequencies also reduce the depth of penetration. In contrast, lower frequencies provide deeper penetration but may reduce sensitivity to small surface-breaking defects. Therefore, selecting a suitable frequency is necessary to balance surface sensitivity and penetration depth. Other factors such as material conductivity, magnetic permeability, temperature, surface coating, probe lift-off, and component geometry may also influence the accuracy and reliability of ECT results [6,7].

ECT has been successfully applied in different industrial sectors, including aircraft maintenance, nuclear reactor heat exchanger inspection, and manufacturing quality control. In aerospace applications, its ability to perform rapid and localized inspection makes it valuable for routine maintenance. However, because aircraft components are made from different materials with different electromagnetic properties, the same testing frequency may not provide the same signal quality for all components. Therefore, experimental evaluation is required to determine the most suitable ECT frequency for each material and inspection condition.

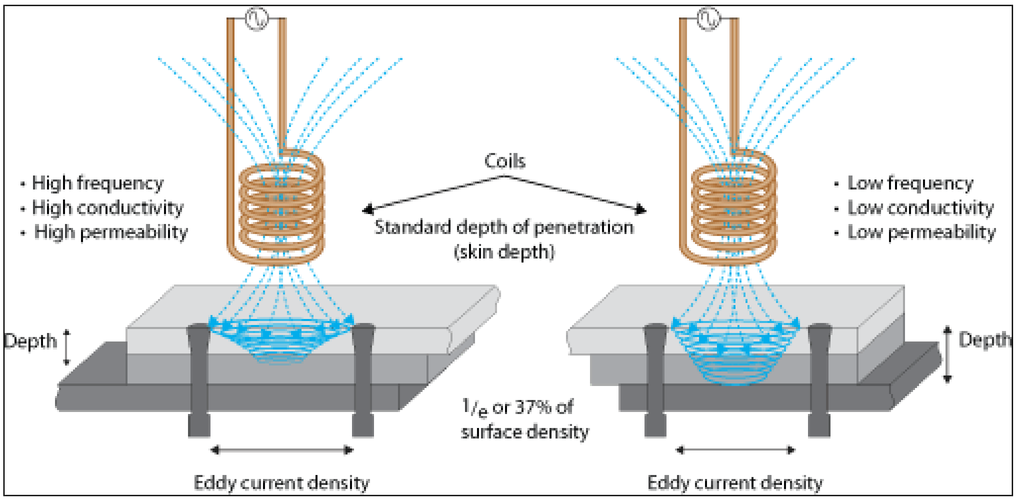


Fig. 3. Applications of low and high frequency Eddy Current Testing (ECT)

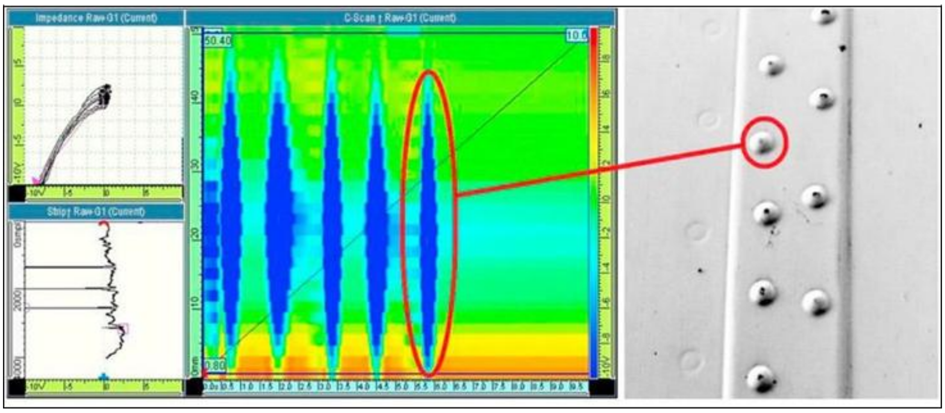


Fig. 4. Inspection of riveted joints using ECT

1.2 Problem Statement

The reliability of Eddy Current Testing in aircraft maintenance depends strongly on the correct selection of inspection parameters, particularly probe frequency. Although ECT is effective for detecting surface and near-surface defects in conductive materials, its performance can be affected by material properties, surface condition, lift-off, coating thickness, geometry, and environmental factors. In aircraft components, these factors may affect signal response and reduce defect-detection accuracy, especially when inspection involves different materials such as aluminum and stainless steel.

Current aircraft inspection practices often focus on critical components such as wheel hubs, landing gear, fastener holes, and airframe structures. However, the most suitable ECT frequency for different aircraft materials is not always clearly defined under actual inspection conditions. Aluminum and stainless steel have different electrical conductivity and magnetic permeability, resulting in different eddy-current responses at the same excitation frequency. Therefore, a frequency that produces a stable, clear response for aluminum may not yield the same result for stainless steel.

Another important limitation of ECT is its restricted depth of penetration. Higher frequencies improve surface sensitivity but reduce penetration depth, while lower frequencies penetrate deeper but may produce weaker responses for small surface flaws. This creates a practical challenge when selecting an inspection frequency for aerospace components, especially when surface defects, near-surface flaws, or coated surfaces are involved. If the frequency is not properly selected, defects may be difficult to identify, or the signal may become unstable.

Therefore, this study evaluates the frequency response of ECT for aluminum and stainless-steel aerospace components using calibration blocks and selected Learjet 24D aircraft components. The inspection focuses on five excitation frequencies, namely 100, 200, 300, 400, and 500 kHz, to determine the frequency that provides the most stable and distinguishable signal response for each material. The findings are expected to support more reliable frequency selection for ECT-based aircraft maintenance inspection.

2. Methodology

This section describes the equipment, calibration standards, aircraft components, and experimental procedure used to evaluate the frequency response of Eddy Current Testing (ECT) for surface flaw detection. The study focused on aluminum and stainless-steel aerospace components using selected frequencies between 100 kHz and 500 kHz. The overall methodology involved equipment preparation, calibration using reference standards, testing on actual aircraft components, signal recording, and comparison of waveform responses.

2.1 Eddy Current Testing Equipment

The ECT inspection was conducted using an Olympus Nortec 600 eddy current flaw detector, as shown in Figure 5(a). The instrument was connected to a right-angle flexible metal shaft surface probe, as shown in Figure 5(b). The Olympus Nortec 600 is a portable eddy current testing unit with a wide frequency range, digital signal processing capability, data storage function, and a high-resolution display. These features make it suitable for detecting surface and near-surface defects in conductive materials commonly used in aerospace, automotive, and manufacturing applications.

The surface probe used in this study was selected because it allows localized inspection of aircraft components with curved or limited-access surfaces. The probe and cable specifications used in the experiment are listed below:

i. Probe: Right-angle flexible metal shaft surface probe, 12.7 cm overall length, 5 mm drop at 90° bend, bridge coil configuration, S/N K00662, P/N 9222164.
ii. Cable: 1.83 m length, bridge coil configuration, 16-pin LEMO to Fischer/LEMO triaxial cable, S/N K00662, P/N 9222164.
iii. Reference standard: Aluminum surface reference block with certified EDM notch depths of 0.203 mm, 0.508 mm, and 1.016 mm, with a maximum notch width of 0.178 mm. The overall block dimension was 25.4 mm × 101.6 mm × 6.35 mm.

(a) (b)

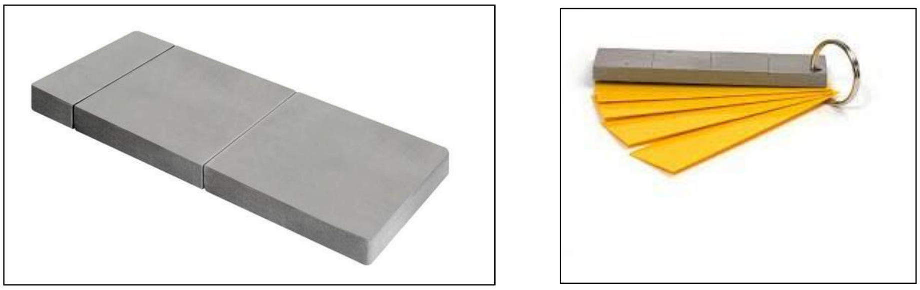
Fig. 5 Eddy current testing equipment used in this study: (a) Olympus Nortec 600 flaw detector and (b) right-angle flexible metal shaft surface probe.

2.2 Calibration and Reference Standards

Before testing the aircraft components, the ECT equipment was calibrated using reference standards. Calibration was necessary to establish a baseline signal response and to ensure that the instrument and probe were functioning consistently before data collection. Two calibration blocks were used in this study: an aluminum calibration block and a stainless-steel calibration block, as shown in Figure 6.

The aluminum calibration block served as the reference for the aluminum aircraft component, while the stainless-steel calibration block served as the reference for the stainless-steel aircraft component. During calibration, the probe was placed on the reference block, and the instrument response was adjusted to achieve a clear, stable waveform. This step was repeated for each selected frequency to ensure that the signal response from the aircraft component could be compared with the corresponding calibration response.

The calibration procedure was conducted carefully to minimize variation due to probe handling, lift-off, and surface contact. For each test, the probe was positioned as consistently as possible on the material surface. The same equipment, probe, and cable were used throughout the experiment to reduce instrument-related variation. Calibration was also repeated during the testing period to confirm the signal's reliability.



(a) (b)

Fig. 6 Calibration standards used in this study: (a) Olympus aluminium reference block and (b) stainless-steel calibration block.

2.3 Aircraft Components and Material Selection

The aircraft selected for this study was the Universiti Tun Hussein Onn Malaysia Learjet 24D, as shown in Figure 7. The Learjet 24D is an all-metal, pressurized, low-wing aircraft with a semi-monocoque fuselage, swept-back wing, and retractable landing gear system. In aircraft maintenance, ECT is commonly used to inspect metallic components such as wheels, hubs, struts, landing gear, airframes, propellers, and engine components for defects such as cracks, fatigue damage, and corrosion.

In this study, two aircraft components were selected for ECT inspection: the wheel hub and the landing gear, as shown in Figure 8. The wheel hub was treated as the aluminum component, while the landing gear was treated as the stainless-steel component. These components were selected because they are important structural and operational parts that may experience cyclic loading, surface wear, fatigue, and corrosion during service.

Fig. 7 Learjet 24D aircraft used as the source of selected aerospace components for ECT inspection.

(a) (b)

Fig. 8 Aircraft components inspected in this study: (a) Learjet 24D wheel hub and (b) landing gear.

2.4 Experimental Procedure

The experiment was conducted to compare the ECT signal response of calibration blocks and actual aircraft components at different excitation frequencies. Five frequencies were selected for testing: 100, 200, 300, 400, and 500 kHz. The frequency range was limited by the available pencil probe and was selected to evaluate changes in waveform stability, signal clarity, and material response.

The experimental procedure followed these steps:

i. The Olympus Nortec 600 was connected to the right-angle flexible surface probe using the specified probe cable.
ii. The instrument was switched on and allowed to stabilize before calibration.
iii. The calibration block was selected according to the material being tested.
iv. The probe was placed on the calibration block, and the baseline waveform was obtained.
v. The test frequency was set to 100 kHz, followed by 200, 300, 400, and 500 kHz.
vi. For each frequency, the waveform response from the calibration block was recorded.
vii. The same frequency was then applied to the corresponding aircraft component.
viii. The waveform response from the aircraft component was recorded and compared with the calibration response.
ix. The procedure was repeated for both aluminum and stainless-steel materials.
x. Measurements were repeated over five consecutive days to observe repeatability and reduce the influence of inconsistent readings.

The overall experimental procedure consisted of equipment preparation, calibration using reference standards, frequency selection, testing on aircraft components, waveform recording, repeatability observation, and comparison of signal responses between the calibration blocks and actual aircraft components.

3. Results and Discussion

This section presents the Eddy Current Testing (ECT) results obtained from the aluminum and stainless-steel calibration blocks and the selected Learjet 24D aircraft components. The analysis focuses on the effect of excitation frequency on waveform stability, signal clarity, and suitability for surface flaw detection. The tested frequencies were limited to 100, 200, 300, 400, and 500 kHz due to the available probe's capability. The results were recorded over five consecutive days to observe repeatability and reduce inconsistencies caused by probe handling, surface contact, or testing conditions.

The main objective of this section is to determine the most suitable frequency for inspecting aluminum and stainless-steel aerospace components. The aluminum calibration block was compared with the aircraft wheel hub, while the stainless-steel calibration block was compared with the landing gear component. The frequency that produced the most stable, distinguishable, and repeatable waveform was considered the most suitable for each material.

3.1 Effects of Testing Frequency on ECT Signal Response

Frequency selection is one of the most important parameters in Eddy Current Testing because it directly affects surface sensitivity and penetration depth. In general, higher frequencies increase sensitivity to surface defects because the induced eddy currents are concentrated near the surface of the material. However, higher frequencies reduce the depth of penetration. In contrast, lower frequencies allow deeper penetration but may produce weaker responses for small surface-breaking defects. Therefore, a suitable frequency must be selected based on the material type, inspection objective, component geometry, and expected defect location.

In this study, the selected frequency range from 100 kHz to 500 kHz was used to evaluate the ECT response on two different aerospace materials. The frequency selection was also influenced by the operating capability of the available pencil probe. Although this range is suitable for surface and near-surface inspection, it limits the ability to evaluate deeper subsurface defects. Therefore, the results should be interpreted as a frequency-response evaluation of surface-flaw detection under the tested conditions.

The use of calibration blocks was important to establish a reference signal before testing the actual aircraft components. Calibration allows the inspector to compare the signal response from a known reference standard with the response obtained from the aircraft component. This process helps to improve consistency and reduces the possibility of misinterpreting signal changes caused by material variation, lift-off, or probe handling [8,9].

3.2 Frequency Response of Aluminium Component

Table 1 compares the aluminium calibration block and the Learjet 24D wheel hub at different excitation frequencies. The waveform response changed noticeably as the frequency increased from 100 kHz to 500 kHz.

At 100 kHz, the waveform was stable but relatively limited in height and definition. The signal response reached approximately the second wave when compared with the calibration block, indicating that the probe could detect material response, but the sensitivity to surface indications was not optimal. At 200 kHz, the waveform became shorter and less pronounced, remaining mostly around the first wave. This suggests that the response at this frequency was weaker and less suitable for clear surface flaw detection.

At 300 kHz, a slight improvement in waveform height was observed. The signal response increased between the first and second waves, indicating greater sensitivity than at 200 kHz. However, the signal was still not as clearly defined as the higher-frequency response. The most stable and distinguishable waveform for the aluminium wheel hub was observed at 400 kHz. At this frequency, the signal was more pronounced and maintained a clearer waveform pattern. This indicates that 400 kHz provided better sensitivity and signal stability for the aluminium component.

At 500 kHz, the waveform became unstable and less consistent. Although higher frequencies normally improve surface sensitivity, excessively high frequencies may increase signal noise, reduce stability, and make interpretation more difficult. For the aluminium wheel hub, 500 kHz appeared to exceed the most effective frequency range under the tested conditions. Therefore, 400 kHz is considered the most suitable frequency for the aluminium aircraft component based on waveform stability and signal clarity [10–13].

Table 1. ECT waveform comparison between aluminium calibration block and Learjet 24D wheel hub at different frequencies.

Frequency	Observed response on aluminium wheel hub	Interpretation
100 kHz	Stable but limited waveform height	Detectable response, but sensitivity is moderate
200 kHz	Shorter and less pronounced waveform	Lower signal clarity
300 kHz	Slight increase in waveform height	Improved response but not optimal
400 kHz	Stable, clear, and more pronounced waveform	Most suitable frequency for aluminum
500 kHz	Erratic and less stable waveform	Reduced reliability for this component

The improved response at 400 kHz can be attributed to aluminium's high electrical conductivity, which allows eddy currents to form effectively near the surface. At this frequency, the balance between surface sensitivity and signal stability was better than at the other tested frequencies.

Although 500 kHz increased the surface concentration of eddy currents, the waveform became less stable, making defect interpretation more difficult.

3.3 Frequency Response of Stainless-Steel Component

Table 2 compares the stainless-steel calibration block and the Learjet 24D landing gear over the same frequency range. Unlike the aluminium component, the stainless-steel landing gear produced weaker waveform responses at lower frequencies and showed clearer improvement at higher frequencies.

At 100 kHz, the waveform was relatively static and confined to the first wave. This indicates that the signal response was weak and insufficiently distinguishable for reliable surface-flaw detection. At 200 kHz, the waveform showed slightly greater movement, but the response was still lower than that of the aluminium component. At 300 kHz, minor waveform changes were observed, but the response remained limited and was similar to the lower-frequency results.

The waveform response became more pronounced at 400 kHz, with greater signal movement and clearer waveform changes. However, the most distinguishable response was obtained at 500 kHz. At this frequency, the waveform showed the highest response and the clearest improvement compared with the lower frequencies. Therefore, 500 kHz is considered the most suitable frequency for the stainless-steel landing gear under the tested condition [14].

Table 2. ECT waveform comparison between the stainless-steel calibration block and the Learjet 24D landing gear at different frequencies.

Frequency	Observed response on stainless-steel landing gear	Interpretation
100 kHz	Static waveform confined near the first wave	Weak surface response
200 kHz	Slight increase in waveform movement	Limited improvement
300 kHz	Minor bumps and low signal clarity	Still not optimal
400 kHz	Higher waveform with larger response	Improved sensitivity
500 kHz	Highest and most distinguishable waveform	Most suitable frequency for stainless steel

The different responses of stainless steel compared with aluminium are mainly due to differences in electrical conductivity and magnetic permeability. Stainless steel generally has lower electrical conductivity than aluminium, which affects the formation and distribution of eddy currents. Therefore, a higher frequency was required to produce a clearer surface response. The result shows that 500 kHz provided the best balance between signal clarity and surface sensitivity for the stainless-steel landing gear.

3.4 Comparison Between Aluminium and Stainless Steel

The results show that material properties strongly influence the optimum ECT frequency. The aluminium component showed the best response at 400 kHz, while the stainless-steel component showed the best response at 500 kHz. This difference indicates that a single testing frequency may not be suitable for all aircraft components, even when the same ECT equipment and probe are used.

For aluminium, 400 kHz produced a stable, well-defined waveform, whereas 500 kHz caused signal instability. This suggests that the signal-to-noise ratio at 500 kHz may be less favourable for the tested aluminium wheel hub. For stainless steel, the signal response increased progressively with frequency, with the clearest response at 500 kHz. Therefore, stainless steel required a higher frequency to produce a distinguishable surface response.

The comparison also confirms the practical importance of calibration before inspection. Calibration using material-specific reference blocks allows the inspector to establish a reliable baseline before testing actual aircraft components. This is especially important because aluminium and stainless steel respond differently to the same excitation frequency. Without proper calibration, signal changes may be misinterpreted as defects or ignored as noise.

Table 3. Summary of suitable ECT frequencies for the tested aerospace components.

Material	Aircraft component	Frequency range tested	Most suitable frequency	Basis of selection
Aluminium	Wheel hub	100–500 kHz	400 kHz	Stable and clearly defined waveform
Stainless steel	Landing gear	100–500 kHz	500 kHz	Highest and most distinguishable waveform

3.5 Repeatability of ECT Measurements

The ECT measurements were recorded over five consecutive days to observe the consistency of the waveform response. Repeated testing is important because ECT signals can be affected by probe position, lift-off, contact pressure, surface condition, operator handling, and environmental variation. By repeating the measurement over several days, the study reduced the possibility of selecting a frequency based on a single, inconsistent reading.

The observed results showed that the general waveform trend remained consistent. For the aluminium wheel hub, the 400 kHz response was repeatedly more stable and distinguishable than the other frequencies. For the stainless-steel landing gear, the 500 kHz response consistently produced the clearest signal. This repeatability supports selecting 400 kHz for aluminium and 500 kHz for stainless steel.

However, the current analysis remains mainly qualitative, as the results were evaluated based on waveform appearance. To further strengthen the reliability of the findings, future analysis should include quantitative signal parameters such as signal amplitude, phase angle, signal-to-noise ratio, mean value, standard deviation, and coefficient of variation. These parameters would allow a statistical comparison of frequencies and provide stronger evidence for determining the optimal inspection frequency.

3.6 Practical Implications for Aircraft Inspection

The findings provide useful guidance for ECT inspection of aluminium and stainless-steel aircraft components. Since aluminium and stainless steel produce different optimum responses, inspection procedures should not apply the same frequency for all materials. Instead, the inspection frequency should be selected based on the component material's electromagnetic properties and verified using an appropriate calibration block.

For aluminium aircraft components such as wheel hubs, 400 kHz is recommended under the tested condition because it produced the most stable and clearly defined waveform. For stainless-steel components such as landing gear, 500 kHz is recommended because it produced the highest and most distinguishable response. These recommended frequencies may help improve inspection reliability, reduce interpretation errors, and support faster maintenance decision-making.

Nevertheless, the findings should be applied carefully. The study focused on selected components and a limited frequency range. The results do not yet represent all aircraft materials, coating conditions, defect depths, or component geometries. Therefore, further validation is needed before the recommended frequencies can be generalized to wider aircraft inspection applications.

3.7 Limitations of the Results

Although the study successfully identified suitable frequencies for the tested aluminium and stainless-steel components, several limitations should be acknowledged. First, the results were based mainly on visual waveform interpretation rather than numerical signal analysis. Second, the study did not quantify defect size, defect depth, or probability of detection. Third, coating thickness, lift-off distance, and surface roughness were not systematically varied. Fourth, the frequency range was limited to 100–500 kHz due to the available probe. Finally, only two aircraft components were tested: the wheel hub and the landing gear.

Therefore, the results should be interpreted as an initial frequency-response evaluation for ECT inspection of selected aircraft components. Future studies should include controlled artificial defects, quantitative signal extraction, statistical analysis, different coating thicknesses, and additional aerospace materials to further validate the findings [15–18].

4. Conclusions

This study evaluated the frequency response of Eddy Current Testing (ECT) for surface flaw detection in selected aluminum and stainless-steel aerospace components. The inspection was conducted using an Olympus Nortec 600 eddy-current flaw detector with a right-angle, flexible metal-shaft surface probe. Aluminum and stainless-steel calibration blocks were used as reference standards before testing selected Learjet 24D aircraft components, namely the wheel hub and landing gear. Five excitation frequencies, 100, 200, 300, 400, and 500 kHz, were investigated to determine the most suitable frequency for each material based on waveform stability, signal clarity, and repeatability.

The results show that the ECT response is strongly influenced by material properties and testing frequency. For the aluminum wheel hub, lower frequencies between 100 and 300 kHz produced weaker and less distinct waveform responses. The most stable and clearly defined signal was obtained at 400 kHz, indicating that this frequency provided the best response for the tested aluminum component. However, the waveform became less stable at 500 kHz, suggesting that an excessively high frequency may reduce signal reliability for this material under the tested conditions.

For the stainless-steel landing gear, the signal response was limited at lower frequencies but improved with increasing frequency. The clearest and most distinguishable waveform was obtained at 500 kHz. This indicates that stainless steel requires a higher testing frequency to achieve a stronger surface response than aluminum. Therefore, based on the observed waveform characteristics, 400 kHz is recommended for aluminum aircraft components, while 500 kHz is recommended for stainless-steel aircraft components under the experimental conditions used in this study.

The findings confirm that proper frequency selection is essential for improving ECT reliability in aircraft inspection. The use of material-specific calibration blocks is also important because aluminum and stainless steel respond differently to the same excitation frequency. In practical aircraft maintenance, using a single frequency for different materials may reduce inspection sensitivity or make signal interpretation difficult. Therefore, the testing frequency should be selected according to the material type, component geometry, expected flaw location, and inspection objective.

Although this study provides useful guidance on frequency selection, several limitations should be acknowledged. The analysis was mainly based on visual waveform interpretation rather than quantitative signal parameters. In addition, defect size, defect depth, coating thickness, lift-off distance, and probability of detection were not fully quantified. The study was also limited to two selected aircraft components and a frequency range of 100–500 kHz due to the available probe capability.

Future work should focus on quantitative analysis of ECT signals by measuring amplitude, phase angle, signal-to-noise ratio, standard deviation, and coefficient of variation. Controlled artificial flaws with known depths and dimensions should be introduced to more accurately evaluate detection sensitivity. Further studies should also investigate the effects of lift-off, coating thickness, surface roughness, probe orientation, and environmental conditions such as temperature and humidity. In addition, the application of ECT to advanced aerospace alloys, multi-layered structures, and composite materials should be explored to improve its adaptability for modern aircraft inspection. The use of advanced probes, multi-frequency ECT, and eddy current array systems may also enhance penetration depth, improve flaw characterization, and support more reliable aircraft maintenance decisions.

Acknowledgement

The authors would like to express their sincere appreciation to the Faculty of Mechanical and Manufacturing Engineering, Universiti Tun Hussein Onn Malaysia, for providing the facilities, equipment, and technical support required to complete this research.

References

[1] B. Karanfiloğlu, N. V. Erden, and E. E. Gültekin, "Inspection of aircraft parts by eddy current method," *International Journal of Aeronautics and Astronautics*, vol. 4, no. 1, pp. 36–42, 2023, doi: 10.55212/ijaa.1310747.

[2] O. Postolache, M. D. Pereira, H. Ramos, and A. Ribeiro, *NDT on Aluminum Aircraft Plates based on Eddy Current Sensing and Image Processing*. 2008. doi: 10.1109/IMTC.2008.4547337.

[3] A. Abdou *et al.*, "An Eddy Current Nondestructive Method for Crack Detection in Multilayer Riveted Structures," *Instrumentation Mesure Métrologie*, vol. 18, pp. 485–490, Nov. 2019, doi: 10.18280/i2m.180508.

[4] A. Sophian and M. Fan, "Pulsed Eddy Current Non-destructive Testing and Evaluation: A Review," *Chinese Journal of Mechanical Engineering*, vol. 30, pp. 500–514, Jun. 2017, doi: 10.1007/s10033-017-0122-4.

[5] M. Janovec, M. Smetana, and M. Bugaj, "Eddy Current Array Inspection of Zlin 142 Fuselage Riveted Joints," *Transportation Research Procedia*, vol. 40, pp. 279–286, Jun. 2019, doi: 10.1016/j.trpro.2019.07.042.

[6] E. E. Gültekin, B. Karanfiloğlu, and N. V. Erden, "Inspection of aircraft parts by eddy current method," *International Journal of Aeronautics and Astronautics*, vol. 4, no. 1, pp. 36–42, 2023, doi: 10.55212/ijaa.1310747.

[7] W. Du, Q. Bai, Y. Wang, and B. Zhang, "Eddy current detection of subsurface defects for additive/subtractive hybrid manufacturing," *The International Journal of Advanced Manufacturing Technology*, vol. 95, no. 9, pp. 3185–3195, 2018, doi: 10.1007/s00170-017-1354-2.

[8] Bauer, F. F., Zechmeister, M., & Reiners, A. (2015). Calibrating Echelle Spectrographs With Fabry-Pérot Etalons. In *Astronomy and Astrophysics*. https://doi.org/10.1051/0004-6361/201526462

[9] Mohseni, E., Habibzadeh Boukani, H., Ramos França, D., & Viens, M. (2019). A Study of the Automated Eddy Current Detection of Cracks in Steel Plates. *Journal of Nondestructive Evaluation*, *39*(1), 6. https://doi.org/10.1007/s10921-019-0647-9

[10] Wan Mohd, W. S., Attan, F., Rifai, D., Ali, K., Sulaiman, M. A., & Mamat, N. H. (2021a). The Effect of Gain and Frequency on Eddy Current Testing for Copper Material Defect Inspection. *IOP Conference Series: Materials Science and Engineering*, *1068*, 012025. https://doi.org/10.1088/1757-899X/1068/1/012025

[11] Wan Mohd, W. S., Attan, F., Rifai, D., Ali, K., Sulaiman, M. A., & Mamat, N. H. (2021b). The Effect of Gain and Frequency on Eddy Current Testing for Copper Material Defect Inspection. *IOP Conference Series: Materials Science and Engineering*, *1068*, 012025. https://doi.org/10.1088/1757-899X/1068/1/012025

[12] Wilken, T., Lovis, C., Manescau, A., Steinmetz, T., Pasquini, L., Curto, G. lo, Hänsch, T. W., Holzwarth, R., &

Udem, T. (2010). High-Precision Calibration of Spectrographs. In *Monthly Notices of the Royal Astronomical Society Letters*. https://doi.org/10.1111/j.1745-3933.2010.00850.x

[13] Khan, S. H., Ali, F., Nusair Khan, A., & Iqbal, M. A. (2008). Eddy current detection of changes in stainless steel after cold reduction. *Computational Materials Science*, *43*(4), 623–628. https://doi.org/10.1016/j.commatsci.2008.01.034

[14] Salmia, S., 1#, F., Sulaiman, & Folly Eldy, E. (2019). Optimisation Frequency for Different Lift off on Aluminium using Eddy Current Testing (ECT) Technique. *Transactions on Science and Technology*, *6*(2-2). https://tost.unise.org/pdfs/vol6/no2-2/6x2-2x191-197.pdf

[15] Steel, M. (2015). *Aluminum vs. Stainless Steel: Benefits of Both In Aviation & Aerospace*. Marlinwire.com. https://www.marlinwire.com/blog/aluminum-vs.-stainless-steel-stainless-steel-in-aviation

[16] Xie, L., Ribeiro, A. L., Alegria, F. C., & Ramos, H. G. (2023). Detection of flaws in austenitic stainless steel plate using eddy current testing. *Research and Review Journal of Nondestructive Testing*, *1*(1). https://doi.org/10.58286/28556

[17] Matúš Geľatko, Hatala, M., František Botko, Radoslav Vandžura, & Jiří Hajnyš. (2022). Eddy Current Testing of Artificial Defects in 316L Stainless Steel Samples Made by Additive Manufacturing Technology. *Materials*, *15*(19), 6783–6783. https://doi.org/10.3390/ma15196783

[18] Matúš Geľatko, Hatala, M., František Botko, Radoslav Vandžura, & Jiří Hajnyš. (2022). Eddy Current Testing of Artificial Defects in 316L Stainless Steel Samples Made by Additive Manufacturing Technology. *Materials*, *15*(19), 6783–6783. https://doi.org/10.3390/ma15196783