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Fracture and failure analysis of the trainer aircraft rudder pedal hanger

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A R T I C L E I N F O

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A B S T R A C T

This study analyzes the T-38A Talon twin-jet trainer aircraft rudder pedal hanger damage due to the fracture that has been identified at the clevis surfaces where the tension rises. The hanger has the function of swinging the rudder pedal under irregular tension loads. The fractured hanger material is magnesium AZ91C-T6 cast. The composition of the hanger is 90% Mg, 8.1–9.3% Al, 0.4–1% Zn, 0.3% Si, 0.13% Mn, 0.10% Cu, and 0.01% Ni. The average hardness value of the material was measured as 77 Hardness Rockwell-C (HRC). The oxygen and chloride pollutants had been observed under Field Emission Scanning Electron Microscope (SEM) and Energy-Dispersive X-ray Spectroscopy (EDX). The mentioned pollutants were considered as the main factors for decreasing the corrosion strength. The mentioned corrosion augmented the crack propagations from multiple origins of the rudder pedal hanger. The fracture and failure analysis results demonstrate that the corrosion pitting associated the fatigue under the influence of repeated loads. Eventually, after the crack had grown catastrophically, the residual cross-section surface could not endure the repeated load overcoming on it, the clevis of the hanger was completely fractured into two pieces.

1. Introduction

An aircraft is a high-tech machine using the application of multidisciplinary engineering sciences and the term “airworthy part” briefly defines that the part is “fit-to-fly”. Only an airworthy part can be inserted into an air vehicle. In terms of airworthiness certification, aircraft are designed for civilian and military purposes. For both of them, their fuselage and equipment are specified for extraordinary operating conditions. Since airworthy part manufacturing, in another meaning, the aviation-grade production needs precise requirements like medical-grade manufacturing, there are some studies focusing on the sensitivity of both industries [1,2].

Military aircraft are designed for operating at more challenging risk levels as dictated by operational needs. In general, they are also required to carry highly explosive ordnance without harming the aircraft itself. It is obvious that, for military and commercial passenger aircraft, the quantity of the task and the level of the risk can differ with the specification of the aircraft [3,4]. These high levels of risks require meticulously prepared and executed validation tests that are ordinated by national/international airworthiness organizations.

Albeit, the prompt validation tests are executed in design, manufacturing, and follow-on-support stages, the unwanted accidents, incidents, and near-misses still may happen due to users behave, environmental conditions, and material defects so on [5]. Undoubtedly, ensuring flight safety is the main and the most vital task of the employee who serves in the aviation industry. Meticulous

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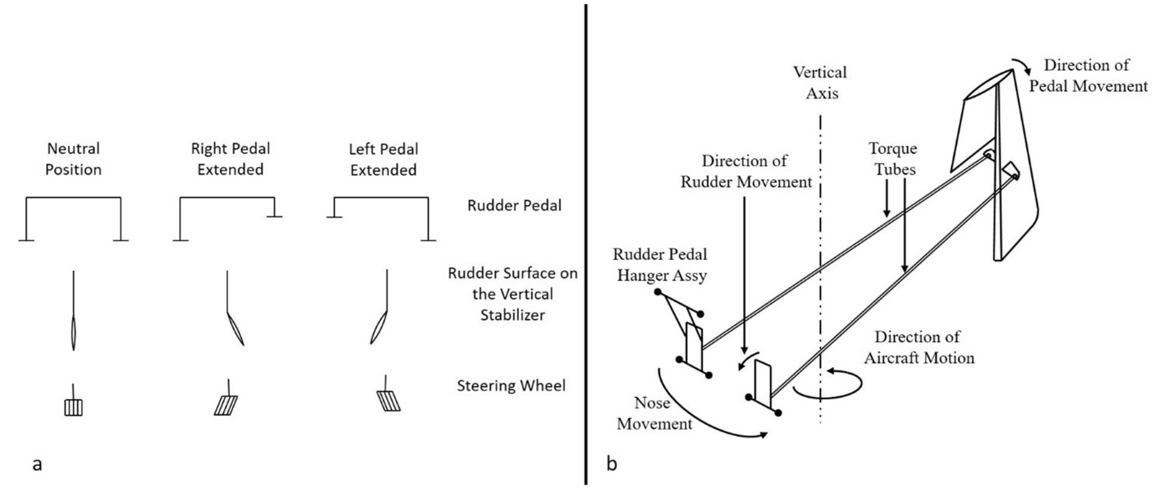

Fig. 1. 1.a. Rudder positions, 1.b. Rudder mechanism and pedal hanger assy.

tests and prompt controls are executed by them in terms of increasing flight safety. Thanks to high-tech detection devices, the nucleation and propagation of the cracks due to material defects sourced by stress concentration have been identified [6]. The results of the analysis are published as technical reports to whom they may concern. Moreover, experts also investigate the fracture-oriented incidents that occurred in the aircraft command systems and release the investigation reports. Some of them become the subject of articles published in national/international journals. With this respect, some of the scientific papers related to the failure analysis of the air vehicles have been reviewed. The mentioned scientific papers in the open literature are given as follow:

D. Trifkovic et al [7] examined the failure analysis of a combat jet aircraft rudder shaft. They determined the heavy corrosion spread over the rudder shaft and pitting corrosion phenomena destroyed 50% of the wall thickness. The material change into a more corrosion-resistant one and maintenance procedure change for more frequent obligatory inspection were suggested.

J. Coronado et al [8] made investigations on the rudder of the McDonnell Douglas MD-80 aircraft, namely DC-9 Super 80. In this study, the holder in the restraining system of the directional rudder was inspected under SEM for fractographic analysis. Also, a Finite Element Model (FEM) was created and analyzed. In conclusion, it was found that the fracture of the holder was due to fatigue of the material originated from a defect in the surface that caused the reduction of fatigue life.

N. Ejaz et al [9] investigated a trainer aircraft crash that had been caused by the rudder cable fracture. It was found that the rudder cable was failed due to a fatigue mechanism. A comparison was done with other directional command system cables. Eventually, it was found that in the regions that rudder cables pass through pulleys there's a 50% of the increased potential of fatigue because of repeated bending under load accompanied by vibration.

F. Bagnoli et al [10] inspected the Piaggio Avant P180 aircraft main landing gear wheel flange. In the paper, it was underlined that many magnesium-based flanges were found cracked during non-destructive inspections in the back shops. Many of these failures were associated with pitting corrosion promoted by fretting other parts that damage the plating. It was also highlighted that porosity in the magnesium casting was found as the origin of the failures.

D.P. Davies et al [11] compared the parts manufactured by magnesium alloys and aluminum alloys on Agusta-Westland Helicopters. They expressed some advice regarding magnesium alloy cast used in the helicopters. In the mentioned paper, it is claimed that the notch sensitivity of magnesium alloy could be a specific factor for fatigue failure occurring especially on the radii area.

After investigating the above-mentioned scientific papers, it was observed that the above-given papers have generally concentrated on the parts other than rudder pedal assembly. In this study, the

T-38A Talon twin-jet trainer aircraft's, rudder pedal hanger is carried out.

2. T-38A Talon Twin-Jet trainer aircraft rudder mechanism and pedal hanger assy

Northrop Corporation started producing T-38A Talon twin-jet trainer aircraft as a twinjet supersonic trainer in 1959 and a total of 1,154 airplanes were manufactured until 1972. As a supersonic jet trainer, the Northrop T-38A Talon twin-jet trainer aircraft is the most widely used model with a total producing number of 1,139 and famous to have many altitude and speed records in its history [12].

2.1. General description of the rudder mechanism

As a foot-operated mechanism, the "rudder and brake" control is one of the primary controls of the aircraft. As the aircraft is airborne, the rudder pedal controls the surface in the vertical stabilizer and its movement towards the sides rotates the aircraft movement called "yaw" whereas taxiing on the ground, the same system is used for steering and brake. When the pilot pushes the right

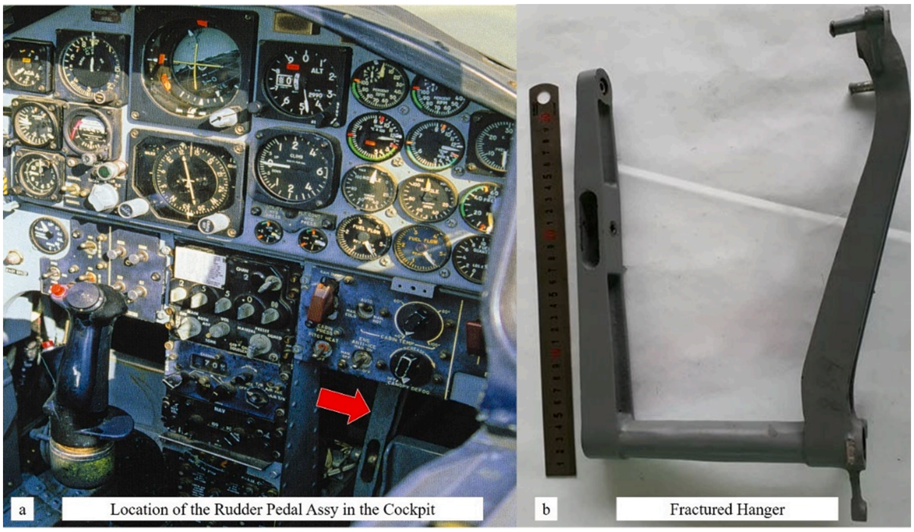

Fig.2. 2.a. Location of the rudder pedal assy in the T-38A Talon twin-jet trainer aircraft, 2.b. Fractured hanger.

Fig. 3. General images about the fracture.

rudder pedal with his heels, the aircraft's nose turns right and synchronically the left rudder comes closer to him by the same displacement. Pedal loads are transmitted to the pedal assembly torque tube through mating offsets on the rudder pedal hanger and the torque arm at their attachment to the torque tube. For breaking on the ground, the balls of the feet are used similarly. Eventually, as illustrated in Fig. 1a., mainly there are three positions of rudder mechanism and in Fig. 1b. aircraft's nose changes direction in the vertical axis for side-to-side [13].

2.2. Rudder pedal hanger assy

The rudder pedal hanger assy is a flight-critical component. When the rudder system fails during the flight, the aircraft only can achieve yaw control only via rolling to generate side force. It should be underlined that, since the sideslip cannot be entirely eliminated, it is barely possible to make the roll, turn, or trim [14]. Literally, the lateral instability due to rudder hanger assy malfunction is an emergency situation.

T-38A Talon twin-jet trainer aircraft's cockpit panel and the rudder assy as shown in Fig. 2a [15] and the removed rudder pedal hanger is shown in Fig 2b.

The main task of the hanger is swinging the pedal. The rudder pedals are swinging oppositely fore-and-aft on hangers supported on a horizontal transverse shaft [16]

3. Material and methodology

During the before take-off check, the pilot terminated the flight because the hanger is fractured during taxiing. Later on, the rudder pedal hanger assy was removed from its place by line maintenance staff. After the first visual check, it was decided to send the rudder pedal hanger assy to the canopy and ejection shop for detailed inspection.

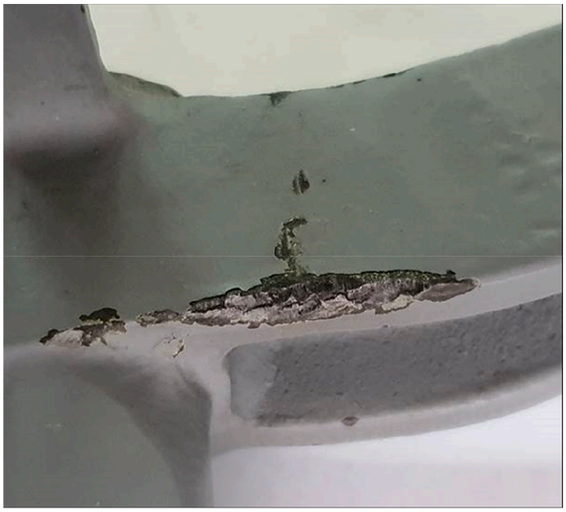

Fig. 4. Ratchet marks on the fractured surface.

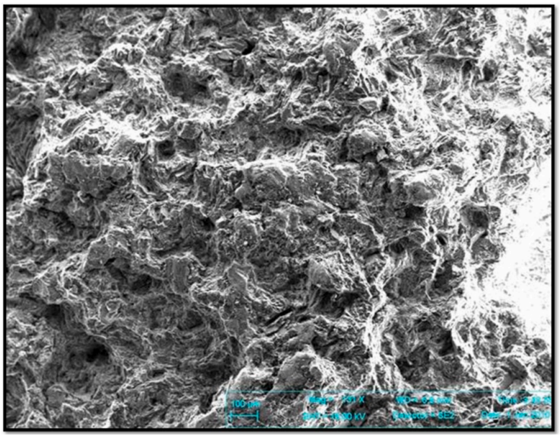

Fig. 5. The micrograph of the corrosion pits.

3.1. Visual analysis

In the "canopy & ejection" shop, the whole rudder pedal assy was disassembled. As shown in Fig. 3., it was observed that the hanger was fractured into two pieces in the clevis where the thickness is relatively narrow and close to the radius section stress concentration is high.

The magnesium AZ 91C-T6 cast is a member of AZ91 alloy family. This family is known with low creep, abrasion resistance, elastic modulus, and ductility besides a high corrosion rate features [17]. It is considered that the hanger was heavily corroded and basically the fracture was based on the corrosion. Also, fretting corrosion was effective.

3.2. Fractographic and metallographic analysis

It was observed that the ratchet marks had been formed by the intersection of fatigue cracks propagation from multiple origins. It was mentioned earlier that the hanger is operated under repeated loads. And it can be claimed that the cracks were intensified by the repeated loads. In Fig. 4. the ratchet marks that are parallel to the overall direction of crack propagation can be visually observed.

During investigations, a sample from the fractured part was metallographically prepared for the optical Field Emission Scanning Electron Microscope (SEM) and Energy-Dispersive X-ray Spectroscopy (EDX) investigations. It was determined that approximately 60% of the fractured surface had a brittle structure along the grain boundaries and cleavage planes with corrosion damage. The pits are shown in Fig. 5. influenced the crack propagation from the origin site towards the zone of hanger clevis where the fracture occurred. It was also observed that, from the lowest point of the crack where the wall thickness decreases, the transverse fracture had started to propagate in both directions and eventually broken the hanger clevis.

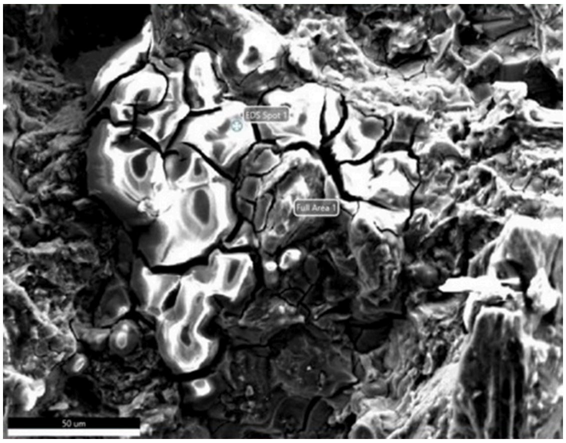

Fig. 6. The corrosion pits formed in the fracture section.

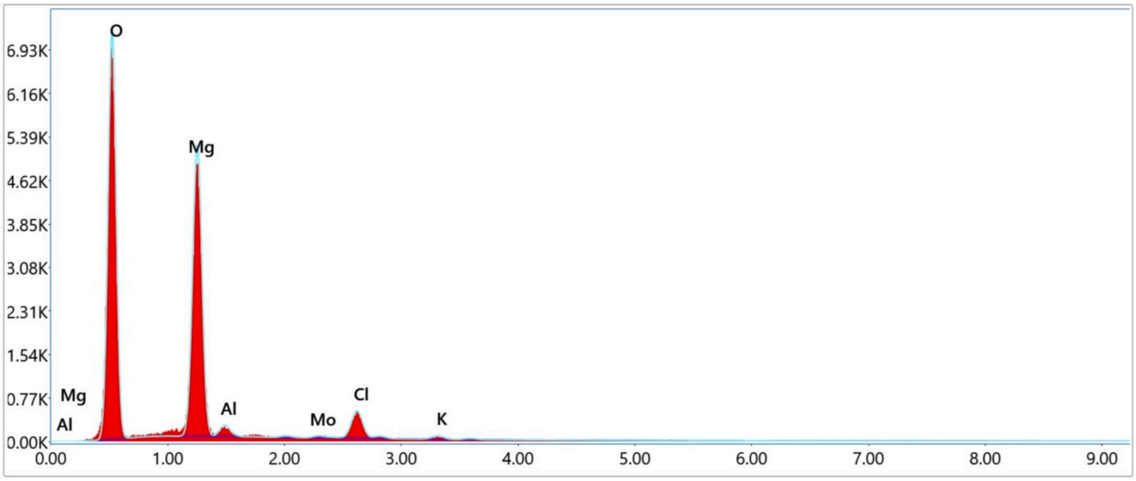

Fig. 7. Element spectrum of the hanger.

After high magnification examination, the remaining surfaces were found to have ductile pits formed by the effect of the repeated load as is shown in Fig. 6.

As a result of the elemental analysis Cl (Chlorine) and element O (Oxygen), which reduce the corrosion resistance, were found on the fracture cross-section surfaces as is shown in Fig. 7.

When the obtained findings are evaluated; from the clevis area of the hanger part where the stress concentration rises, it was concluded that the ambient atmosphere and time combination suffered corrosion damage and the remaining section was broken by not enduring the repeated loads.

4. Discussion

Upon the investigations the results of the analysis are given as follow:

- In the visual analysis, it is figured out that the rudder pedal hanger was mechanically broken into two parts on the clevis area where repeated loads are effective.
- Some other minor cracks and ratchet marks were intensively observed that are nucleated from multiple crack propagation.
- The hanger was originally produced by material magnesium AZ91C-T6 cast.
- Magnesium AZ91C-T6 cast provides excellent castability, high damping capacity, and easy machining. On the other hand, the mentioned cast process brought complications because of low abrasion resistance and high corrosion rate.

Obviously, comparing to magnesium alloys, aluminum alloys are more preferable with their high micro-hardness and wear-resistance. In this manner, a cross-check investigation was performed for switching the material from magnesium to aluminum.

Table 1
The specifications for cast magnesium alloys cast versus aluminum alloy cast [18]

Features	Mg alloy cast	Al alloy cast
Density (g/cm^3)	1.75–1.87	2.5–2.9
Yield strength (MPa)	70–215	50–330
Specific strength	37–123	17–132
Elastic modulus (GPa)	42–47	72–89
Specific stiffness	22–27	25–36
Elongation (% strain)	1–10	0.4–10
Melting point (°C)	447–649	475–677

The purpose of the study was to prevent any future incidents that might be originated from the low wear-resistance of the rudder pedal hanger.

During post investigations, to avoid lack of abrasion resistance, the “Aluminum Alloy A201-TT” became a robust candidate for replacing the material of the hanger. Table 1 sums up, some important specifications of magnesium alloy cast and aluminum alloy cast.

From Table 1, it can be figured out that aluminum alloy cast has advantages over magnesium alloy cast in terms of elastic modulus, yield strength, specific strength, and elongation. On the other hand for overall evaluation through the material selection phase, the price and reachability are also key indicators.

In terms of widely usage on the air vehicle.

5. Conclusion

Based on the visual, fractographic, and metallographic investigations of the rudder pedal hanger the following conclusions are given as follow;

- The rudder pedal hanger fracture seems to be originated from corrosion pitting and it was promoted Fatigue Crack Propagation (FCP).
- 60% of the fractured surface was heavily corroded because of the high level of oxygen and chlorine.
- The remaining cross-section surface of the hanger’s clevis could not carry the repeated load.
- Finally, the hanger was entirely fractured into two pieces by repeated loads.

In conclusion, the mechanical type scratching damages and chlorine-rich corrosion pits are determined as the root cause of the fracture failure.

To avoid future similar failures the following preventions and measures were taken;

- The maintenance staff was informed for controlling the remaining hangers with magnesium alloy.
- The remaining rudder pedal hangers were controlled for mechanical damages and imperfections.
- The hanger’s material changed from Magnesium Alloy AZ91C-T6 cast into more corrosion-resistant material as Aluminum Alloy A201-TT.
- A new type of hangers are installed following the TCTO (Time Compliance Technical Order).

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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