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Structural Analysis of Embraer Erj-145xr Aircraft Rudder

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ABSTRACT

The rudder is a vital control surface located on the vertical stabilizer that manages an aircraft's yawing moment. While traditional designs rely heavily on aluminum alloys, modern aviation demands a shift toward materials that optimize weight without compromising structural integrity. This project focuses on the detailed modeling and comparative structural analysis of the Embraer ERJ-145XR rudder to identify an optimal material composition. The methodology involved creating a high-fidelity 3D model of the rudder structure—comprising ribs, spars, and skin—using CATIA V5 R20. Static stress analysis was then performed using ANSYS to evaluate the performance of three distinct materials: Aluminum 2024-T4 alloy, Glass Fiber Reinforced Polymer (GFRP), and Carbon Fiber Reinforced Polymer (CFRP). The analysis accounted for critical flight conditions, specifically focusing on aerodynamic and gust loads. Results from the finite element approach provided a detailed comparison of deformation, von-Mises stresses, and total mass across the selected materials. The study demonstrates that while aluminum remains a reliable standard, composite materials like CFRP offer significantly higher specific strength and rigidity, potentially leading to a 10–20% weight reduction in primary structures. By analyzing these factors, the project successfully identifies a lightweight yet durable structural configuration that optimizes the load path for aerodynamic forces. Ultimately, this research provides a framework for reducing manufacturing and maintenance costs through informed material selection in the early stages of aircraft design.

Keywords: Embraer ERJ-145XR, Aluminum 2024-T4 Alloy, CFRP, GFRP, CFD

1. INTRODUCTION

It presents a detailed structural analysis of the aircraft rudder for the Embraer ERJ-145XR, focusing on optimizing its design through material composition. The rudder is a primary control surface mounted on the symmetrical vertical stabilizer, responsible for controlling the aircraft's yawing moment. It consists of structural elements like ribs, which maintain the airfoil shape and provide stability, as well as spars and skin. When the rudder moves, it creates a pressure difference over the stabilizer, generating the torque necessary for rotation about the aircraft's center of gravity.

Traditionally, commercial aircraft utilize semi-monocoque structures made primarily of aluminum alloys. While these designs are highly refined, the aviation industry faces increasing pressure to maximize weight and cost efficiencies for competitive and environmental reasons. Conventional metal designs have reached a point where significant further weight savings are difficult to achieve. In contrast, advanced materials like Carbon Fiber Reinforced Plastics (CFRP) offer specific strength values five to six times higher and specific rigidity two to three times higher than standard aluminum alloys. Despite this, the full potential of composites is often not realized due to conventional airframe layouts. This study aims to address the need for optimal, minimum-weight rudder designs by evaluating alternative materials such as Glass Fiber Reinforced Polymer (GFRP) and CFRP alongside traditional Aluminum 2024-T4. The research utilizes CATIA V5 R20 for the high-fidelity 3D modeling of the rudder components. The analysis is conducted using ANSYS software, where static stress analysis is performed to determine safety factors and identify critical stress points under specific loading conditions. The load calculations consider both aerodynamic forces and gust loads, specifically the high-speed gust conditions defined by FAR 25 regulations. The rudder itself is essential for maintaining proper alignment during maneuvers, such as banking turns initiated by ailerons or spoilers. Without correct rudder input, an aircraft might experience adverse yaw or increased drag. By applying different material properties in a simulated environment, this project seeks to provide a durable, lightweight structure that efficiently distributes aerodynamic forces to the airframe while reducing overall mass and manufacturing costs. This investigation into the Embraer ERJ-145XR's rudder provides critical insights for designers and researchers looking to enhance regional jet performance through advanced structural analysis. The goal is to arrive at an optimal design by systematically modifying the material composition of the rudder while ensuring it can withstand acting loads.

This optimization is crucial because experimental testing of vertical tail structures is a complex and expensive process, making numerical simulation an essential tool in modern aeronautical engineering.

1.1. The Role of the Rudder in Aircraft Control

The rudder is a primary control surface mounted on the symmetrical vertical stabilizer of an aircraft. Its fundamental purpose is to control the yawing moment, which is the rotation of the aircraft about its vertical axis. The rudder structure is typically composed of three main internal components:

- **Spars:** These run spanwise and act as the main support, carrying flight loads and resisting twisting loads that could otherwise cause material failure.
- **Ribs:** These maintain the precise aerodynamic airfoil shape of the rudder while providing internal stability against loads encountered during flight maneuvers.
- **Skin:** This external surface carries loads from the wings and empennage and helps distribute aerodynamic forces to the airframe.

Contrary to common perception, the rudder is not used to turn the aircraft in flight; turns are primarily achieved by banking using ailerons or spoilers. Instead, the rudder ensures the aircraft remains properly aligned with its curved flight path, preventing adverse yaw and unnecessary drag. It operates by changing the effective shape of the vertical stabilizer's airfoil, thereby altering the lift generated by the stabilizer in a sideways direction.

1.2. Importance of Structural Analysis and Optimization

Environmental and economic pressures require future aircraft designs to maximize weight and cost efficiencies to remain competitive and safe. As traditional metal designs have reached a high level of maturity, significant new weight savings are unlikely to come from aluminum alone. This project addresses the industry's rising demand for minimizing maintenance and product costs through optimized material selection in the early design stages. The structural analysis in this study specifically considers gust loads and aerodynamic loads. For the Embraer ERJ-145XR, the load was calculated based on Federal Aviation Regulation (FAR) 25 specifications, resulting in a design load of approximately 4772.4 N acting on the rudder at cruise speed.

1.3. Material Composition and Comparison

A major focus of the report is the comparative analysis of three different materials to determine which offers the best strength-to-weight ratio for the rudder:

1.3.1. Aluminum 2024-T4 Alloy: A high-strength alloy traditionally used in projects requiring excellent fatigue resistance and a reliable strength-to-weight ratio.

1.3.2. Glass Fiber Reinforced Polymer (GFRP): A composite material that is more flexible than carbon fiber but stronger than many metals by weight. It is non-magnetic, chemically inert, and can be molded into complex shapes.

1.3.3. Carbon Fiber Reinforced Polymer (CFRP): Advanced composites that offer specific strength 5 to 6 times higher and specific rigidity 2 to 3 times higher than aluminum alloys, though current conventional use often only realizes a 10–20% weight benefit.

2. LITERATURE SURVEY

A literature review is a critical survey of scholarly sources on a specific topic, providing an overview of current knowledge and identifying research gaps. For this project, the authors analyzed six distinct research and journal papers to inform their decisions regarding rudder dimensions and material selection.

2.1. Key Research Findings and Comparisons

The following studies were central to the project's background:

2.1.1. Fighter Aircraft Optimization: Gaur and Tengli (2015) addressed the structural analysis of an optimized rudder for an F-16 fighter aircraft. Their research specifically evaluated the potential of an Al-0.5%Sc alloy as an alternative to the standard Al 2024-T3 alloy, using ANSYS for deformation and von Mises stress analysis.

2.1.2. Weight Optimization via Composites: Moses et al. (2015) reviewed aircraft empennage structures, concluding that composite structures are superior to metallic ones in terms of weight, which directly influences overall airplane performance.

2.1.3. Static Analysis of Transport Tails: Vinayaka et al. (2015) conducted a linear static analysis of a transport aircraft’s vertical tail using Al 7075-T6 alloy. Their work focused on finding safety factors for different rudder deflections using finite element approaches like MSC/PATRAN and MSC/NASTRAN.

2.1.4. Lightweight Aircraft Design: Ahamed et al. (2014) performed weight optimization on the empennage of light aircraft, such as Zenith models. They noted that while both metallic and composite skins have unique advantages, reducing operating costs through weight reduction is essential for market competitiveness.

2.1.5. Educational Algorithms and New Configurations: Al-Shamma et al. (2017) introduced a rudder sizing algorithm for transport aircraft to aid engineering students. Additionally, Anoosha et al. (2018) explored modifying the Airbus A320 NEO with a winglet-rudder configuration to assist in severe crosswind landings (up to 50 knots), proving that such designs can reduce primary rudder loads.

2.2. Material Evolution and Contemporary Practices

The report highlights that traditional aircraft fuselages utilize aluminum semi-monocoque structures due to the metal's isotropic properties. However, because metal designs have reached a high degree of perfection, significant future weight savings are unlikely. The industry is shifting toward Carbon Fiber Reinforced Plastics (CFRP), which possess specific strengths 5 to 6 times higher than aluminium alloys. While current CFRP applications often only yield a 10–20% weight benefit, more advanced configurations, such as the composite lattice structures developed by CRISM in the 1980s, offer even higher efficiency.

This literature survey establishes that while aluminium is a reliable standard, the integration of advanced composites and computational analysis tools like CATIA and ANSYS is necessary to achieve the weight and performance optimizations required by modern regional jets like the ERJ-145XR.

3. METHODOLOGY

The methodology for the structural analysis of the Embraer ERJ-145XR aircraft rudder involves a systematic process ranging from mathematical load estimation and 3D geometric modeling to comparative finite element analysis (FEA) using multiple materials. The primary objective is to evaluate whether advanced composite materials can optimize the weight of the rudder structure while maintaining high structural integrity.

3.1. Load Calculation and Aerodynamic Requirements

The first phase of the methodology involves determining the external forces acting on the rudder. The project utilizes the V-n Diagram for Gust Envelope to analyze flight limits based on FAR 25 regulations.

3.1.1. Gust Load Determination: The analysis focuses on cruise speed (V_E = 231.4 m/s) and considers a high-speed gust velocity (u_E) of 15.25 m/s.

3.1.2. Aerodynamic Load Formula: The increase in tailplane load (Δ P) is calculated using the formula:

$$\Delta P = 0.5 \times \rho o \times V_E \times S_T \times \frac{dC_{L,T}}{d\alpha} \times \mu_E$$

Where ρo is air density (1.225 kg/m³), and S_T is the tailplane surface area (18.4$ m²).

3.1.3. Resulting Load: Based on statistical data for the ERJ-145XR, the total load acting on the rudder is calculated to be 4772.4 N.

3.2. Geometric Modeling using CATIA V5 R20

The structural modeling is conducted using CATIA V5 R20, focusing on the primary components: ribs, spars, and skin.

3.2.1. Airfoil Selection: The design employs NACA 6 Series airfoils. Specifically, the NACA 64A010 is used at the root of the rudder, while the NACA 64A012 is used at the tip.

3.2.2. Structural Assembly:

- **Ribs:** These are modeled to maintain the airfoil shape and provide stability against acting loads.
- **Spars:** Modeled as the main spanwise support to carry flight loads and withstand twisting forces.
- **Skin:** The external surface that carries aerodynamic loads and distributes them to the internal framework.

3.2.3. Final Assembly: The model includes a series of ribs and spars integrated with the stressed skin to form a complete, high-fidelity rudder assembly.

3.3. Material Selection for Comparison

To achieve weight optimization, the methodology compares a traditional metallic alloy with advanced composites:

3.3.1. Aluminium 2024-T4: Chosen for its high strength-to-weight ratio and fatigue resistance, serving as the baseline material.

3.3.2. Carbon Fiber Reinforced Polymer (CFRP): Selected for its exceptional specific strength (5–6 times higher than aluminium) and rigidity.

3.3.3. Glass Fiber Reinforced Polymer (GFRP): Included as a cost-effective, flexible composite alternative that is stronger than many metals by weight.

3.4. Structural Analysis in ANSYS

The finalized CATIA model is exported to ANSYS for static structural analysis.

- **Meshing:** A detailed mesh is generated for the rudder surface to ensure accurate stress distribution results.
- **Boundary Conditions:**
  - **Constraints:** Fixed supports are applied to simulate the hinges connecting the rudder to the vertical stabilizer.
  - **Loading:** The calculated air load of 4772.4 N is applied perpendicular to the rudder surface.
- **Simulation Parameters:** The software calculates Total Deformation, Equivalent (von-Mises) Stress, and Maximum Principal Stress for each of the three materials.

3.5. Evaluation and Optimization

The final step is the comparative evaluation of results. The methodology focuses on identifying which material yields the minimum mass while keeping stress levels within the safety factor of the structure. By comparing the deformation and stress patterns of CFRP and GFRP against the baseline Aluminium 2024-T4, the project determines the most efficient material for a lightweight, durable rudder.

4. RESULTS AND DISCUSSION

The analysis focuses on evaluating the structural performance of the Embraer ERJ-145XR aircraft rudder. The primary objective was to compare three different materials—Aluminum 2024-T4 alloy, Glass Fiber Reinforced Polymer (GFRP), and Carbon Fiber Reinforced Polymer (CFRP)—to determine the most efficient material for optimizing weight while maintaining structural integrity.

4.1. Load Calculation Methodology

The analysis began with determining the loads acting on the rudder structure. This was achieved using a V-n diagram for Gust Envelope based on FAR 25 regulations.

4.1.1. Operating Conditions: The analysis was conducted at a cruise speed (V_E) of 231.4 m/s.

4.1.2. Gust Parameters: A high-speed gust velocity (u_E) of 15.25 m/s was utilized for the load calculation.

4.1.3. Aerodynamic Factors: The air density (ρo) was set at 1.225 kg/m³, and the tailplane surface area (S_T) was 18.4 m².

4.1.4. Calculated Load: Using the rate of change of tailplane lift coefficient ($dC_{L,T}/d\alpha = 0.12$), the total load acting on the rudder (ΔP) was calculated as 4772.4 N.

4.2. Finite Element Analysis (FEA) Setup

The structural analysis was performed using **ANSYS 19.2** software.

4.2.1. Modeling: The 3D geometry of the rudder, including ribs and skin with a thickness of 3mm, was modeled in CATIA V5 R20 and imported into ANSYS.

4.2.2. Boundary Conditions: A fixed support was applied to the root airfoil of the rudder. The calculated aerodynamic force of 4772.4 N was applied perpendicular to the rudder surface.

4.2.3. Meshing: The model was discretized into finite elements to accurately estimate stresses and deformations.

4.3. Material-Specific Analysis and Results

The report provides a detailed breakdown of results for each material type under the same loading conditions:

4.3.1. Aluminum 2024-T4 Alloy

This material is the conventional choice due to its high strength-to-weight ratio and excellent fatigue resistance.

- **Properties**: Density of 2780 kg/m³ and Young’s Modulus of 73 GPa.
- **Structural Performance**:
  - **Total Deformation**: 3.7153 mm.
  - **Equivalent (von-Mises) Stress**: 13.504 MPa.
  - **Maximum Principal Stress**: 15.118 MPa.
  - **Total Mass**: 13.593 kg.

4.3.2. Epoxy S Glass UD (GFRP)

GFRP was analyzed as a potential composite alternative.

- **Properties**: Density of 2000 kg/m³.

- **Structural Performance**:

○ **Total Deformation**: 5.9084 mm (higher than aluminum due to lower stiffness).
○ **Equivalent (von-Mises) Stress**: 13.243 MPa.
○ **Maximum Principal Stress**: 15.228 MPa.
○ **Total Mass**: 9.7794 kg.

4.3.3. Epoxy Carbon UD (CFRP)

CFRP represents the advanced material option, known for having a specific strength 5 to 6 times higher than aluminum alloys.

- **Properties**: Density of 1490 kg/m³.
- **Structural Performance**:

○ **Total Deformation**: 1.1147 mm (lowest deformation, indicating highest rigidity).
○ **Equivalent (von-Mises) Stress**: 12.636 MPa.
○ **Maximum Principal Stress**: 15.239 MPa.
○ **Total Mass**: 7.5147 kg.

4.4. Comparative Results and Weight Optimization

The results clearly demonstrate the advantages of using composite materials for aircraft secondary structures like rudders.

Material	**Total Mass (kg)**	**Total Deformation (mm)**	**Equivalent Stress (MPa)**
Al 2024-T4	13.593	3.7153	13.504
GFRP	9.7794	5.9084	13.243
CFRP	7.5147	1.1147	12.636

4.5. Discussion of Findings

The analysis reveals that CFRP (Epoxy Carbon UD) is the most efficient material for the ERJ-145XR rudder. It achieved a mass reduction of approximately 44.7% compared to traditional aluminum, while also providing the highest stiffness, evidenced by the lowest total deformation of 1.1147 mm. GFRP also showed a significant weight reduction of 28.2% compared to aluminum but resulted in higher deformation. All stresses calculated for the three materials were within safe operating limits, confirming the structural viability of the optimized designs

5. CONCLUSIONS

As a vital primary control surface, the rudder manages the aircraft's yawing moment by creating pressure differences across the vertical stabilizer. The modeling process utilized CATIA V5 R20 to create a detailed representation of the internal structural components, including the ribs, spars, and skin.

The research concludes that the transition from traditional aluminum alloys to advanced composite materials like CFRP is essential for the future of aeronautical engineering. While Aluminum 2024-T4 remains a benchmark for its isotropic properties and cost-effectiveness, the significant weight reduction offered by CFRP directly enhances aircraft fuel efficiency and payload capacity.

By successfully demonstrating that an optimized composite rudder can maintain structural safety under severe gust loads while reducing mass by nearly 45%, this project provides a technical foundation for implementing lightweight primary structures in regional jet families like the Embraer ERJ-145XR. This shift not only aligns with environmental goals to reduce carbon emissions but also ensures air transport remains economically competitive.

Key Findings and Results

The comparative analysis across the three materials yielded significant insights into weight optimization and structural performance:

- **Weight Reduction**: CFRP emerged as the most efficient material for weight savings. Compared to the baseline Aluminum 2024-T4, Epoxy Carbon UD (CFRP) achieved a mass reduction of approximately 44.7%. Epoxy S Glass UD (GFRP) provided a 28.2% reduction.
- **Structural Integrity**: Static stress tests confirmed that the stresses generated in the rudder structure under aerodynamic loads remained well within the safety margins for all materials. CFRP demonstrated the highest specific rigidity, ensuring the structure could withstand bending, torsion, and compression without excessive deformation.
- **Deformation Performance**: The analysis tracked total and directional deformation to ensure airfoil shape retention during maneuvers. Composite materials exhibited predictable and manageable deformation levels consistent with high-performance aviation standards.

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