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Structural Analysis and Optimization of Aircraft Rudder

Deepak Gaur¹, Dr. P. N. Tengli²

Senior Research Assistant, Aeronautical Development Establishment Campus, DRDO, Bengaluru, Karnataka, India¹

Scientist 'G', Aeronautical Development Establishment Campus, DRDO, Bengaluru, Karnataka, India²

ABSTRACT: One of the important structural component of the aircraft is rudder which controls the yawing moment. Aircraft rudder, which is mounted on the vertical stabilizer of the aircraft, is made up of structural components like ribs, spars, and skin. Usually, a single C-cross section airfoil shaped spar is used for the rudder design which runs along the rudder length. It is the major load bearing member in the aircraft rudder. In this research an attempt has been made to explain the optimized rudder design and its structural analysis. MIL-F-8785C standard is referred for determination of load acting on the aircraft rudder, its distribution throughout, and for optimization. For the design and analysis, gust load and aerodynamic load acting on the aircraft rudder is taken into consideration. For the design modification, a small percentage of Scandium (Sc) is added in Aluminium (Al) alloy composition which is analysed in terms of yield strength and results were compared with respect to that of standard Aluminium rudder.

KEYWORDS: Von Mises stress, MIL-F-8785C, C-cross section, Optimization.

I. INTRODUCTION

The research presented in this paper addresses the structural analysis of the optimized rudder control surface for the fighter aircraft. Objective is to model, analyse and arrive at the optimal design by modifying the material composition of the aircraft rudder. Rudder, one of the main control surface in an aircraft controls the yawing moment. Rudder is mounted on the symmetrical vertical stabilizer of the aircraft, is made up of structural components like ribs, spars, and skin. It is a C-shape single spar construction with ribs located along the aircraft rudder. Ribs maintains the airfoil shape for the rudder while providing stability to the structure of the aircraft rudder against the acting loads during manoeuvres. Movement of rudder on either side generates a pressure difference over the aircraft stabilizer, leading to the generation of yaw moment. For the design and analysis, gust load and aerodynamic load acting on the aircraft rudder is taken into consideration.

Material selection in construction of an aircraft is quite complex as it is more of a trade-off between low density, high strength, and ease of processing or fabrication. Selection of aircraft materials for various part of the structure depends on different criteria which depends on the operational requirements, and constraints of the aircraft and its structural members. Some of the most important requirements are fabrication characteristics, fatigue strength, corrosion, brittleness, environmental stability, fracture toughness, compatibility with other materials, crack growth rate, availability, and cost.

Because of its light weight and corrosion resistance properties, Aluminium (Al) alloy, especially Al 2024-T3 alloy, is widely used in aerospace manufacturing and fabrication. Aluminium alloy offers one-third density as compared to the steel alloys along with tensile strength ranging between 70-700 MPa. Thus, lightweight characteristic of the aluminium alloy does not affect its strength.

Scandium (Sc) metal is lighter than majority of the metals. Also, it offers good corrosion resistance, good response to anodization process, superior weld integrity, high melting point of 1541 °C, and comparative low density as of aluminium. For producing pure scandium, Scandium Fluoride (ScF₃) is heated with Calcium (Ca) metal.

The application of aluminium-scandium (Al-Sc) alloy is usually found in design and fabrication of sports equipment, especially baseball bat. Till date, its use has not been observed in aerospace industry. Metallurgical tests have shown

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higher strength to weight ratio, corrosion resistance, durability, and thermal capacity for Al-Sc alloy in comparison with standard Al 2024-T3 alloy. Tests have shown 150% increase in yield strength along with highest increase in tensile strength, and high fatigue characteristics with specific strength resembling that of Titanium (Ti), while Sc is used in 0.1-0.5% proportion in Al-Sc alloy. Also, on comparing with Al 2024-T3 alloy which is most widely used in aerospace industry, Al-Sc alloy has proven to offer high strength and fracture toughness. These exceptional results offered by Al-Sc alloy is the main reason for this research where application of Al-Sc alloy is tested on the aircraft rudder results in terms of strength is compared with that of the rudder made of standard Al 2024-T3 alloy.

For the optimization of the rudder design, scandium is used in small quantities with the aluminium alloy in order to minimize the structural weight without compromising the structural yield strength. Introduction of scandium resulted in optimization of structural efficiency by minimization of weight. The rudder optimization is carried out at every stage of the development phase.

For the calculation of load and skin thickness, MIL-F-8785C is taken as standard, which is analysed in the later stages. SOLIDWORKS® software is used for modelling rudder and vertical stabilizer. Depending on the nature of load acting, a high strength to weight ratio material is chosen for design and fabrication of the optimized aircraft rudder. For the structural analysis ANSYS WORKBENCH® software is used.

The work in this paper is divided in three stages. 1) Modelling 2) Load calculation 3) Optimization and Analysis. Modelling of aircraft rudder and vertical stabilizer is done through SOLIDWORKS® software. MIL-F-8785C standard is referred for determining load, especially, pressure load, gust load, and manoeuvring load acting on the aircraft rudder and vertical stabilizer which are required for design and analysis purposes. For the optimization and analysis stage, first SOLIDWORKS® model is imported to ANSYS WORKBENCH® software. Then mass optimization and shape optimization are carried out for rudder design along with static structural analysis for multiple cases of rudder design comprising of combination of Al 2024-T3 alloy material, and Al-0.5%Sc alloy material as rudder material for non-deflected rudder, and deflected rudder cases. At last, results are compared for multiple cases.

Paper is organized as follows. Section II describes modelling of aircraft rudder and vertical stabilizer. Calculation of loads are carried out and results are presented in Section III. Section IV presents optimization of aircraft rudder. In Section V static structural analysis is carried out on the optimized design for different scenarios. Comparative results are presented in Section VI. Finally, Section VII presents conclusion.

II. MODELLING

Dimensions of the rudder of F-16 fighter aircraft are used for modelling rudder along with horizontal stabilizer in SOLIDWORKS® software.

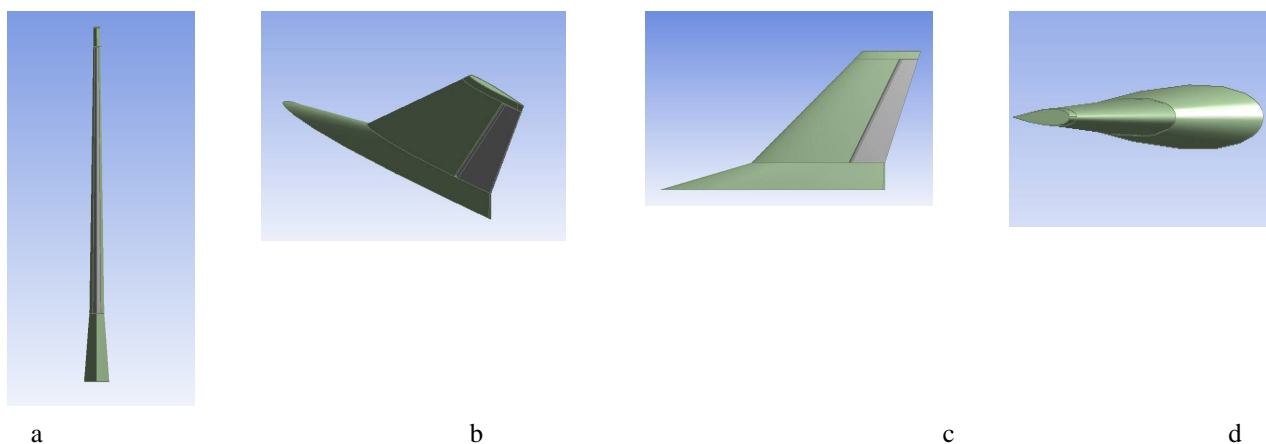


Figure 1. Modelling (a) Front view of aircraft rudder and horizontal stabilizer (b) Top view Front view of aircraft rudder and horizontal stabilizer (c) Isometric view Front view of aircraft rudder and horizontal stabilizer (d) Side view Front view of aircraft rudder and horizontal stabilizer

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III. LOAD CALCULATIONS

For calculation of load on aircraft rudder and vertical stabilizer, MIL-F-8785C specifications are taken as standard. For rudder and vertical stabilizer design and analysis purpose, gust load, pressure load, and manoeuvring load are taken into consideration.

Table 1. Data for load calculation

Parameters	Value
Mass of the aircraft (W)	16,875 Kg
Wing surface area (S)	27.87 m ²
Altitude (h)	12,192 m
Density (ρ)	0.3016 Kg/m ³
Speed of sound (a)	295.07 m/sec
Mach number (M)	0.8
Manoeuvre load factor (n_x)	6
Gust load factor (n_z)	3

Table 2. Calculated load values

Load	Value
Manoeuvring load (P_m)	19,176.04 N/m ²
Gust load (P_g)	9,588.022 N/m ²
Pressure load (P_p)	8,402.986 N/m ²
Total load (P_{total})	37,167.048 N/m ²

IV. OPTIMIZATION

For optimization of aircraft rudder, SOLIDWORKS® model is imported to ANSYS WORKBENCH® software. Two optimizations, mass optimization and shape optimizations, are carried on the existing model in ANSYS WORKBENCH® software to improve the efficiency.

Mass optimization is carried to reduce the weight of the aircraft rudder. For this, tip chord length and root chord length of aircraft rudder are given as boundary conditions. Changes in the tip chord length automatically changes root chord length and vice-versa. Possible outcomes are presented in table 3. Thus, the length values of the aircraft rudder are optimized or scaled down, eventually resulting in mass optimization of aircraft rudder.

Table 3. Mass optimization of aircraft rudder

S. No.	Root Chord Length (mm)	Tip chord length (mm)	Mass (Kg)	Equivalent Stress (N/m ²)
1	271	153	85.705	6.1954E+08
2	243.9	153	85.065	8.1145E+08
3	271	137.7	85.412	9.2366E+08
4	243.9	137.7	84.771	7.1783E+08
5	298.1	137.7	86.05	6.3099E+08
6	243.9	168.3	85.358	7.6345E+08
7	298.1	168.3	86.635	8.019E+08

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Thus, mass optimization resulted in scaling down of rudder weight by 84.771 Kg, for corresponding equivalent stress of $7.1783E+08$ N/m², and for most optimized combination of root chord length and tip chord length of the aircraft rudder.

Shape optimization is done by removing the excess material from the structure of the rudder which in turn reduces or optimizes the weight of the rudder.

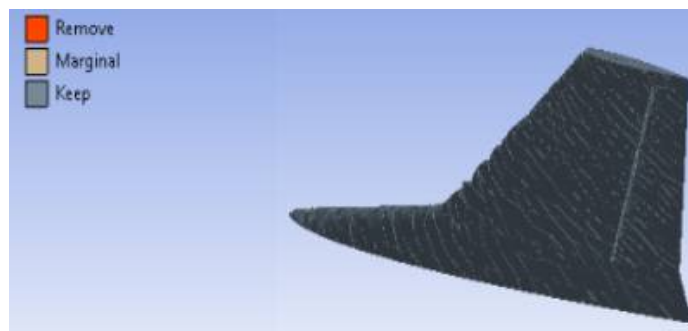


Figure 2. Shape optimized aircraft rudder and vertical stabilizer

Table 4. Shape optimized results for aircraft rudder

Original Mass	214.990 kg
Marginal Mass	1.788 kg
Optimized Mass	181.260 kg

Shape optimization resulted in reduction of original mass of the aircraft rudder by 15.68% i.e., 33.73 Kg for 20% fixed target reduction case. This reduction in rudder mass is substantial and contributes to the reduction in overall weight of the aircraft, thus resulting in improvement in fuel efficiency of the aircraft.

V. STATIC STRUCTURAL ANALYSIS

Static structural analysis is carried out for different conditions on the optimized design, like change in material composition, non-deflected rudder, and the deflected rudder in order to determine two factors, Von-Mises Stress which tells whether a given material will yield or fracture, and Total Deformation which is a temporary self-reversing change in shape, once the force is removed.

A. Analysis for Von-Mises Stress and Total Deformation for Al 2024-T3, and Al-0.5%Sc as rudder material for non-deflected rudder case

Table 5. Von-Mises stress result for Al 2024-T3 as rudder material for non-deflected rudder

Maximum	232.030 MN/m ²
Minimum	2.9304E-006 MN/m ²

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Table 6. Von-Mises stress result for Al Al-0.5%Sc as rudder material for non-deflected rudder

Maximum	199.660 MN/m ²
Minimum	2.4866E-008 MN/m ²

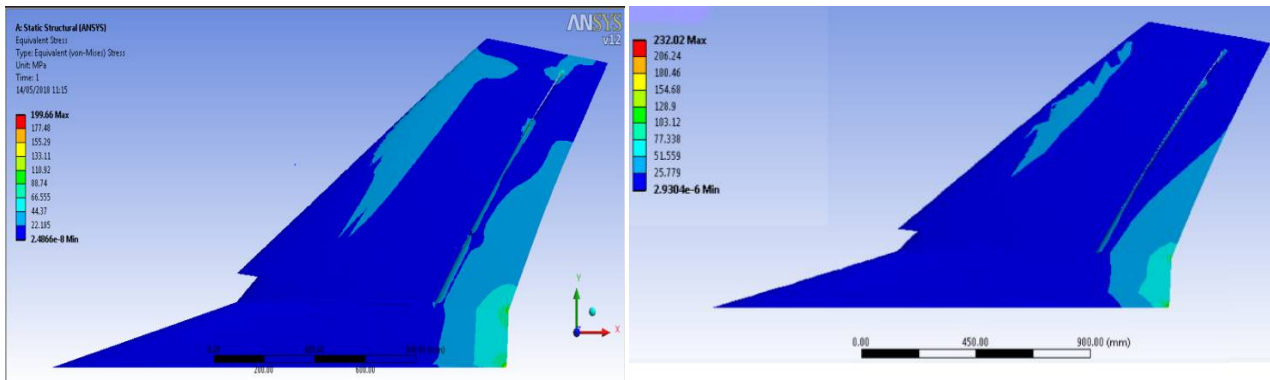


Figure 3. Von-Mises stress. (a) Al 2024-T3 as rudder material for non-deflected rudder (b) Al-0.5%Sc as rudder material for non-deflected rudder

Table 7. Total Deformation result for Al 2024-T3 as rudder material for non-deflected rudder

Maximum	1.375 mm
Minimum	0 mm

Table 8. Total Deformation result for Al-0.5%Sc as rudder material for non-deflected rudder

Maximum	0.591 mm
Minimum	0 mm

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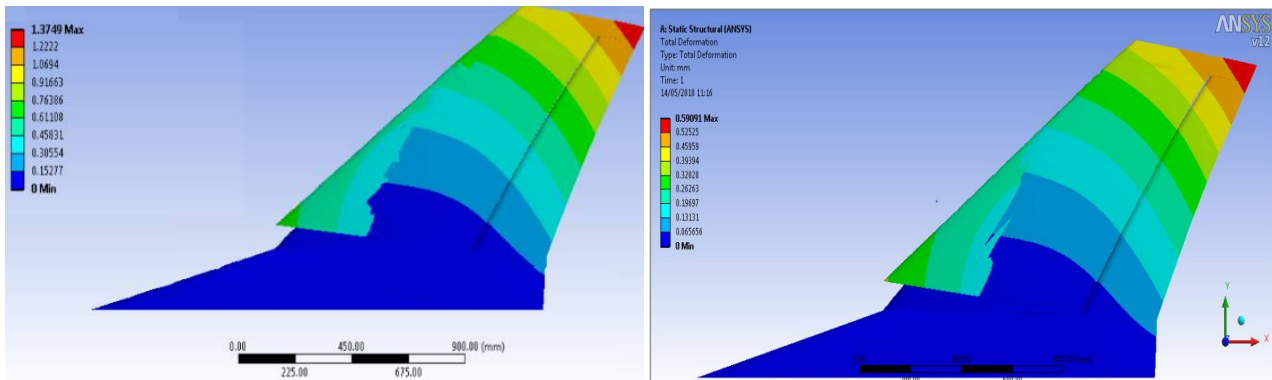


Figure 3. Total Deformation. (c) Al 2024-T3 as rudder material for non-deflected rudder (d) Al-0.5%Sc as rudder material for non-deflected rudder

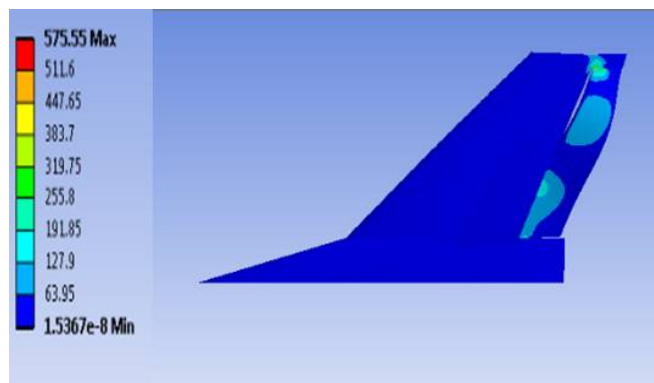
Analysis for Von-Mises Stress and Total Deformation for Al 2024-T3, and Al-0.5%Sc as rudder material for deflected rudder case

Table 9. Von-Mises stress result for Al 2024-T3 as rudder material for deflected rudder

Maximum	162.410 MN/m ²
Minimum	3.6468E-006 MN/m ²

Table 10. Von-Mises stress result for Al Al-0.5%Sc as rudder material for deflected rudder

Maximum	125.550 MN/m ²
Minimum	1.5367E-008 MN/m ²



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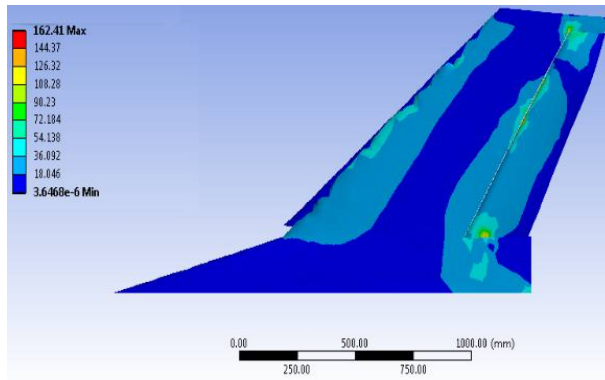


Figure 4. Von-Mises stress. (a) Al 2024-T3 as rudder material for deflected rudder (b) Al-0.5%Sc as rudder material for deflected rudder

Table 11. Total Deformation result for Al 2024-T3 as rudder material for deflected rudder

Maximum	3.583 mm
Minimum	0 mm

Table 12. Total Deformation result for Al-0.5%Sc as rudder material for deflected rudder

Maximum	3.411 mm
Minimum	0 mm

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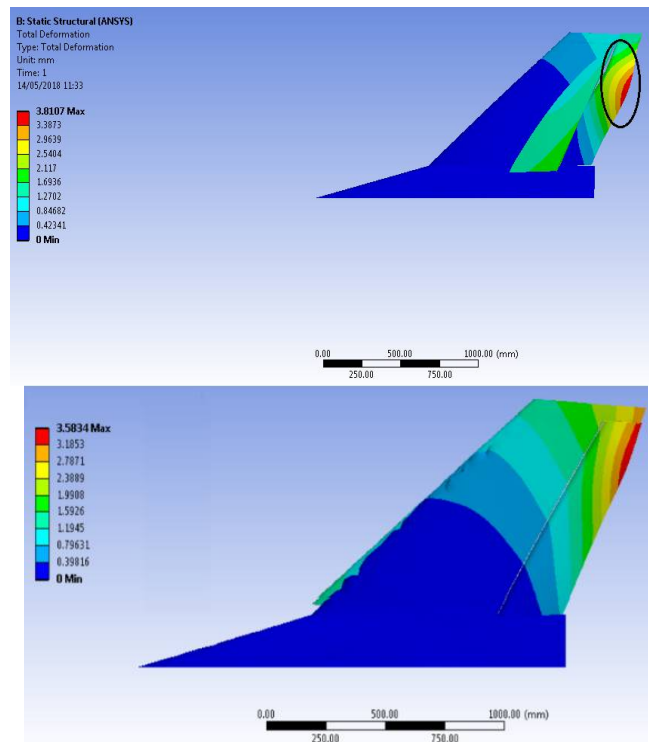


Figure 4. Total Deformation. (c) Al 2024-T3 as rudder material for deflected rudder (d) Al-0.5%Sc as rudder material for deflected rudder

VI. RESULTS

The comparative static structural analysis has been carried out in between the optimized rudder made of Al 2024-T3 alloy, and Al-0.5%Sc alloy for non-deflected and deflected rudder cases. Following results are presented in table 13.

Table 13. Comparative results

Material		Al 2024-T3	Al-0.5%Sc
Non-deflected Rudder	Von Mises stress	Maximum	232.030 MN/m ²
		Minimum	2.9304E-006 MN/m ²
	Deformation	Maximum	1.375 mm
		Minimum	0 mm
Deflected Rudder	Von Mises stress	Maximum	162.410 MN/m ²
		Minimum	3.6468E-006 MN/m ²
	Deformation	Maximum	3.583 mm
		Minimum	0 mm

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On comparing the results obtained from the tests for multiple cases it is observed that maximum and minimum values of Von-Mises stress and deformation comes out to be lesser for Al-0.5%Sc alloy in comparison with standard Al 2024-T3 alloy for both non-deflected and deflected rudder cases.

VII. CONCLUSION

In the current research, application of Al-0.5%Sc alloy is evaluated for the optimized design and fabrication of yaw control surface in the aircraft - the rudder. The rudder is first optimized in terms of weight to improve the efficiency. Structural analysis is then carried out on the optimized rudder for both Al 2024-T3, and Al-0.5%Sc alloys. Test results showed potential application of Al-0.5%Sc alloy over Al 2024-T3 alloy in optimal design and fabrication of aircraft rudder.

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