International Journal of Research in Engineering and Science (IJRES)
ISSN (Online): 2320-9364, ISSN (Print): 2320-9356
www.ijres.org Volume 13 Issue 5 ǁ May 2025 ǁ PP. 120-126

Dynamic Transient Analysis and Structural Weight Reduction of an Aircraft Wing using HyperMesh

Mr. Arvind Raj
*[*1]Assistant Professor Department of Aeronautical Engineering, Global Academy of Technology, Bengaluru, Karnataka*
Gagan M U
[2]Department of Aeronautical Engineering, Global Academy of Technology, Bengaluru, Karnataka
Hemanth Gowda M
[3]Department of Aeronautical Engineering, Global Academy of Technology, Bengaluru, Karnataka
Nandeesh V
[4]Department of Aeronautical Engineering, Global Academy of Technology, Bengaluru, Karnataka

Abstract:
An aircraft wing always sees the fluctuation in air for quite some time during the flight, and even sudden gusts of wind produce such rapid and unsteady variations in the forces that act on it. This project studies the dynamic behavior of an aircraft wing structure subjected to various gust loads at velocities of 2, 5, 10, and 20 m/s. Emulating the NASA CS (2)-0714 airfoil, an aluminium wing was selected for its high structural strength and light weight. Transient (time-domain) analysis performed for the stress and displacement of the wing under short-duration gusts (of the order of 5-10 seconds) using software like HyperMesh for meshing and OptiStruct for solving. A V-n diagram is also created to give a better picture of the way the wing behaved under various loads. The results are useful in designing wings that would manage real-life turbulence more efficiently and improve flight safety.

Keywords: *Transient Analysis, Gust Load Simulation, Wing Structural Analysis, NASA CS(2)-0714 Airfoil, Finite Element Method (FEM), OptiStruct Solver, HyperMesh Meshing, Structural Response, Displacement and Stress Analysis, Time-Dependent Loading, Gust Envelope*

Date of Submission: 06-05-2025 Date of acceptance: 17-05-2025

I. INTRODUCTION

Standard aircraft wings experience such dynamic loads as gusts, which cause sudden stress and deformation at conditions that cannot be predicted by static analysis. This study, therefore, explores the dynamic response of a tapered wing using NASA CS(2)-0714 airfoil under various gust velocities towards structural safety, especially in transient conditions. The model is, however, developed in CATIA, meshed in HyperMesh, then analyzed using OptiStruct to obtain the evolution of time-dependent stress and displacement. The results are interpreted using a V-n diagram to obtain safe flight envelopes while ensuring more accurate and resilient wing design practices.

1.1.1 Background

The literature on dynamic transient analysis of wing structures has matured considerably in the last twenty years with the new computational techniques and insights into aeroelastic phenomena. During its flight, an aircraft system is subjected to a variety of aerodynamic loads, among which gust loads are possibly the most important transient loads acting on wings. Such loads arise from sudden changes in the speed of airflow, which cause stress variations, structural deformations, and, possibly, fatigue failures. Traditional static load assessment does not incorporate time-dependent expressions for gust loads, and hence, the behavior of wings under actual conditions necessitates transient dynamic analysis.

Aircraft fly through quickly changing atmospheric conditions. Although there are different considerations affecting flight performance and safety, gust loads are of paramount importance as they exert sudden forces that tend to induce flexural motion in the wings and possibly cause some long-term damage. Whereas the conventional design procedure tends to study static load cases, these dynamic situations are very much expected to be disregarded. Hence, the important thing to understand is how the wing sees a gust event utilizing its transient structural response, which is, in other words, its response in time to the sudden application and subsequent removal of a load**.**

1.1.2 Purpose of Study

The project's main aim is the investigation of an aircraft wing's reaction to short-duration gusts of different intensities. The dynamic simulation should identify critical stress points in the wing, the time behavior of displacement, and if the design could withstand ultimate gust scenarios without being unsafe.

With an understanding of transient effects, engineers can design safer, more efficient aircraft. That is particularly relevant in the case of modern airplanes, which nowadays are expected to operate in environments considered to be broad and usually unpredictable.

II. LITERATURE REVIEW

Research on aircraft wing behavior under varying operational and environmental loads has assumed great importance due to the aforementioned demand for light but resilient structures capable of withstanding dynamic conditions. Prior research had concentrated on optimization in terms of materials, evaluation of the structural response under static and dynamic forces, and an analysis of newly developed propulsion configurations that affect load distribution.

As noted, Jamil et al. studied the design and structural aerodynamics of a fiber-reinforced expanded polystyrene wing for UAV applications. The study utilized a coupled fluid-structure interaction (FSI) approach to analyze the wing’s response to aerodynamic loading. The study gave the airflow and structural displacement perturbation, and it was able to capture pressure distribution and displacement phenomena intricately. To enhance optimization, the authors performed a limitation of weight while increasing stiffness and durability through design of experiments (DoE) techniques to minimize weight while keeping stiffness and durability in check. Their results exemplify the importance of an integrated analysis approach to the design of lightweight composites for unmanned aircraft.

The study by Madhu and Pavan Kadole focuses on the analysis of static and dynamic performance on the metallic wing of an aircraft. Their work incorporated 3D CAD design along with finite element stress analysis to determine the natural frequency, modal shape, and stress distribution of the structures. In performing static analysis, the concentration of stress was found adjacent to the root. In dynamic analysis, it was also found that the rates of oscillation shapes or contours of several predominant modes of vibration, especially during harmonic excitation, alter the position of the structure. The authors pointed out that the blending of these interactions is paramount for structural assurance for flight operations to avert any possibility of resonance.

Schubert et al. have contributed further to the assessment of fundamental flight loads by studying the effects of gust and landing loads concerning propeller-mounted wings. It was shown that the particular type of propulsion system has additional aerodynamic and structural problems to solve, especially during transient phenomena. The study noted that gusts and hard landings impose severe load oscillations, particularly around the engine nacelles, and therefore must be addressed in propeller-mounted wing design. The authors suggested that the configuration for advanced aircraft needs a more systematic approach to the evaluation of the load cases during the design process.

As a whole, these studies lay the groundwork for studying the aerodynamic phenomena of the response of a wing to a sudden change in load. They demonstrate the need for hybrid structural analysis that incorporates the principles of material dynamics, mode shapes, and new engine installation, all of which drive the taper wing structural response study in this research.

III. METHODOLOGY

1.3.1 Overview

A simulation-based approach was initiated to characterize the wing response due to different gust load conditions. The process involved an airfoil selection, the design of a 3D wing rib model, application of material properties, and transient structural analysis using FEA tools. Considerable attention was given to the gust simulation that realistically affects the performance capability of flight.

1.3.2 Airfoil Selection

A multi-airfoil configuration spans the entire length of the wing to attain aerodynamic efficiency and structural performance. The NASA SC (2)-0714 airfoil is used at the root due to its comparatively thicker shape and higher camber, which help bear high bending moments and provide good lift characteristics near the fuselage. The mid-span section moving outward uses a NASA SC (2)-0612 airfoil, a profile that is well-balanced for maintaining lift and structural continuity. A NASA SC (2)-0510 airfoil is used at the outboard section because of its slender form and thin profile, keeping the weight of the wingtip low to minimize induced drag. With this spanwise variation, the lift distribution is optimized, stall characteristics are improved, and aerodynamic efficiency is enhanced. The gradual reduction of thickness along the span, from root to tip, is a design feature allowing for controlled, progressive stall from the root, thus enhancing safe handling characteristics during flight maneuvers.

The root section (near the fuselage) typically has a thicker airfoil, i.e., NASA SC (2)-0714, to handle higher structural loads and provide better lift distribution. The mid-span section transitions to a slightly thinner airfoil, i.e., NASA SC (2)-0612, which balances lift and reduces drag. The tip section (near the winglet) has an even thinner airfoil, i.e., NASA SC (2)-0510, to minimize drag and control wingtip vortices, which improves fuel efficiency.

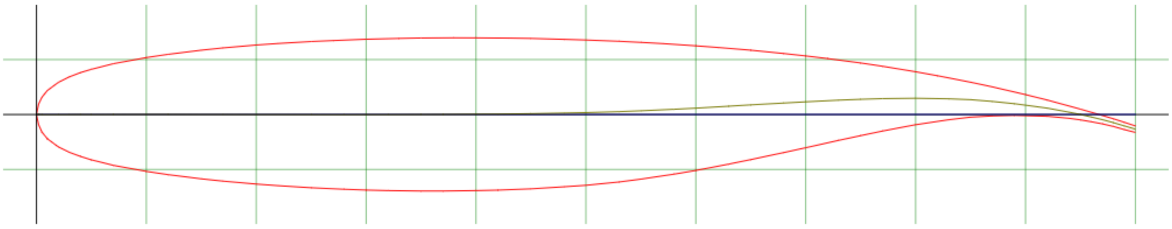


Figure 1 : NASA SC(2)-0714

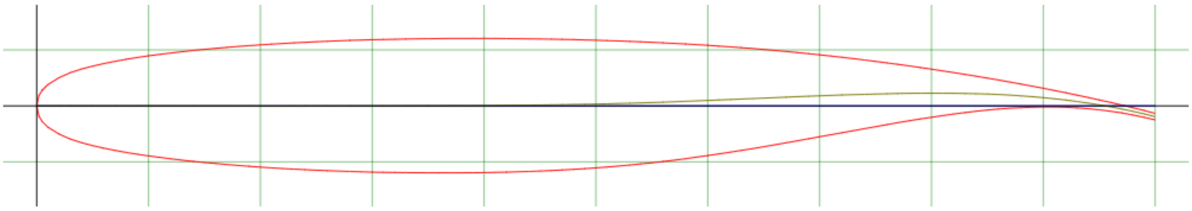


Figure 2 : NASA SC(2)-0612

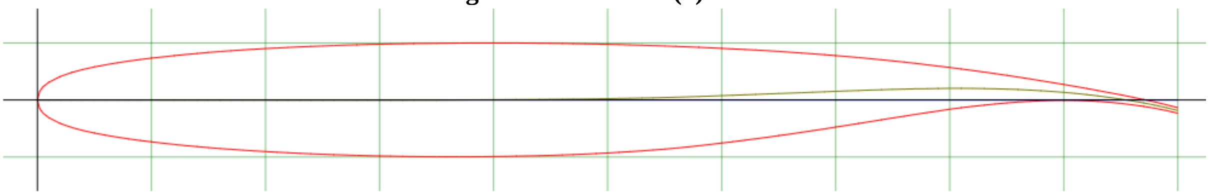


Figure 3 : NASA SC(2)-0510

1.3.3 Wing Geometry

The wing is very tapered and formed with ribs and spars to simulate a more realistic aircraft wing box. The thicker airfoils at the root give the required structural depth to resist bending loads while tapering toward the tip, which greatly reduces structural weight while maintaining a level of integrity. Aluminum alloy is readily welcomed as the material of choice due to its good strength-to-weight ratio, high fatigue resistance, and ease of fabrication. Rib cross-sections along the span conform to airfoil profiles, while globally the structure has been designed to effectively transfer aerodynamic and inertial loads throughout the wing, particularly during dynamic gusting scenarios. Thus, the aerodynamic shaping along with structural planning ensures that the wing sustains efficiency and survivability over a range of flight conditions.

PARAMETERS	VALUES
Wing Span	14180mm
Sweep Angle	25 deg
Rib Thickness	5mm
Spar Thickness	17.5mm
Rib Spacing	800-900mm
Material	Aluminium 2024

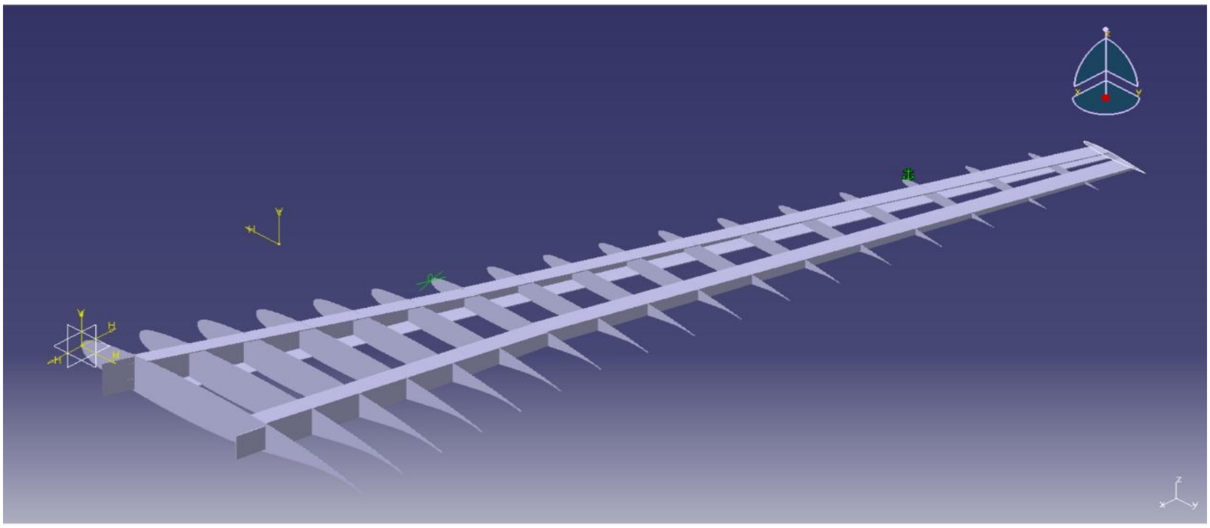


Figure 4 : Wing Geometry (i)

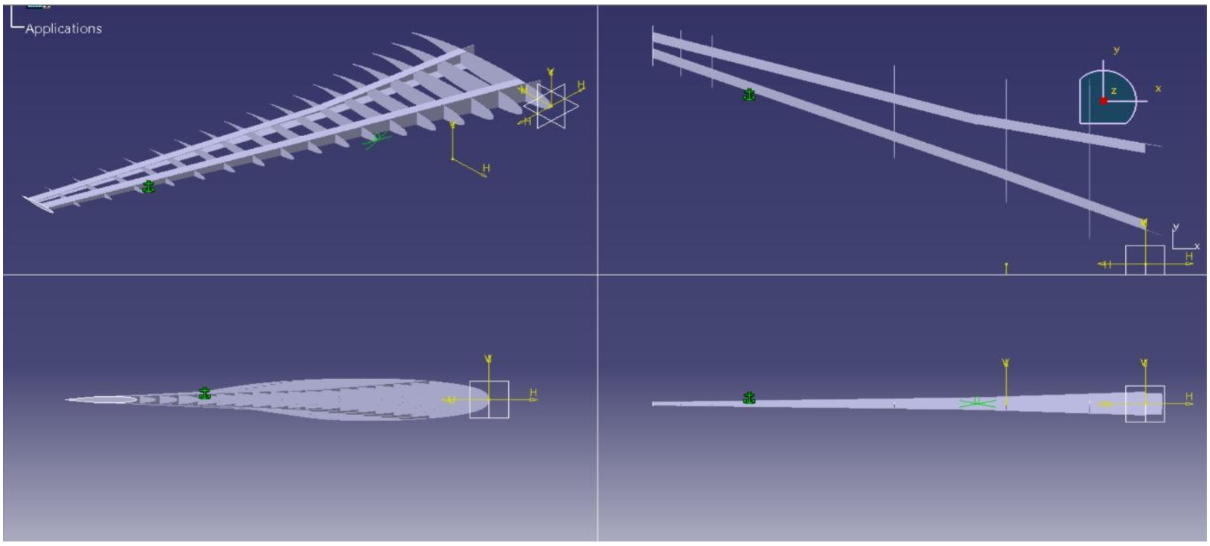


Figure 5 : Wing Geometry (ii)

1.3.4 Gust Load Cases

There are four discrete gust load cases: 2, 5, 10, and 20 m/s to simulate real-world flight conditions. Each gust velocity is applied following the standard 1-cosine profile, which introduces a transient loading in time. The period of application is between 5 and 10 seconds, according to the regulatory standards (for example, FAR 25.341) and realistic atmospheric conditions, which might cause transient aerodynamic loads as well.

1.3.5 Software and Solver

The initially constructed wing model with spanwise variation of airfoil sections wins a compliment from CATIA V5 because it gives control over smooth shaping and structural configurations. The next step is to transfer to HyperMesh, and sophisticated meshing tools are used to create a tetrahedral mesh very densely in areas sensitive to forces, like the intersection of the wing root and spar. Quality checks are made on mesh uniformity and aspect ratio control to eliminate almost all chances of numerical instability in analysis. The entire process of the numerical simulation is done in OptiStruct, an Altair solver, recognized for its efficiency and effectiveness in the transient dynamic structural analysis. Therefore, OptiStruct is used to give a qualified measure over time under gust loading on stress, displacement, and modal response. It is fitted with modern time-stepping algorithms and damping models, delivering the inertia of structures and energy absorption.

1.3.6 Simulation Setup

In the simulation environment, the root is clamped along all degrees of freedom, replicating attachment to the fuselage. Gust loads are scaled up by a transient surface pressure on the upper surface of the wing by applying a 1-cosine profile. The loading is introduced over a predefined time interval (5 to 10 seconds) for gust speeds 2, 5, 10, and 20 m/s. Material properties such as density, Young's modulus, and Poisson's ratio for aluminum follow aerospace standards. A damping ratio of 2% was applied to prepare a realistic vibrational decay. Datasets will later be collected for time-dependent analysis, including nodal displacement, element stress, and deformation modes.

IV. RESULT AND DISCUSSION

The results obtained are as discussed below

1.4.1 Mesh Quality Evaluation

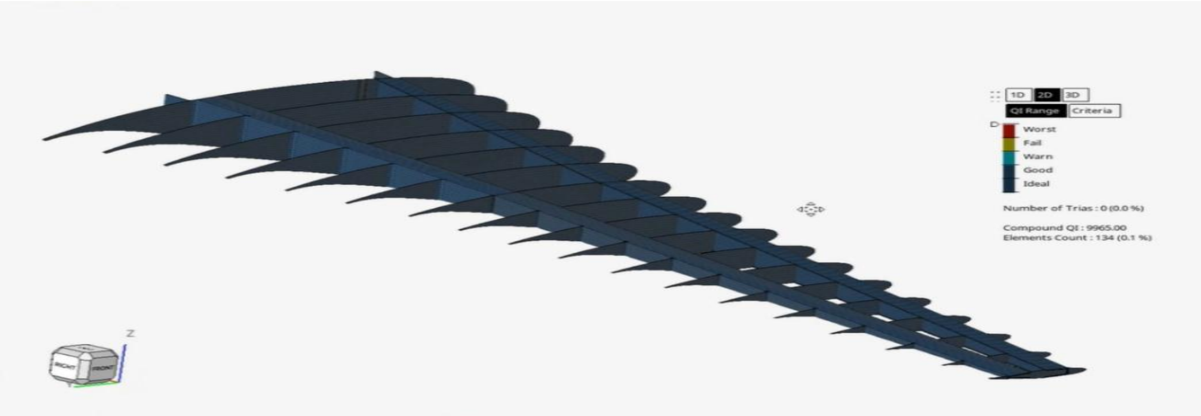


Figure 6: Wing Meshing

For the truly transient analysis, a quality check of the mesh was done using HyperMesh before simulating to ensure accuracy and stability in results. The model is made up of 9965.00, only 134 elements (0.1%) in the "warn" category, while the majority are either rated as "good" or "ideal". Mostly, it was tetrahedral elements, but finer refinement has been done at the wing root, rib junctions, and leading edges since stress concentration is expected at these junctions. The elements under the fail or worst categories guarantee the passage of quality checks, thus giving reliable finite element model simulations.

1.4.2 Stress and Displacement Analysis

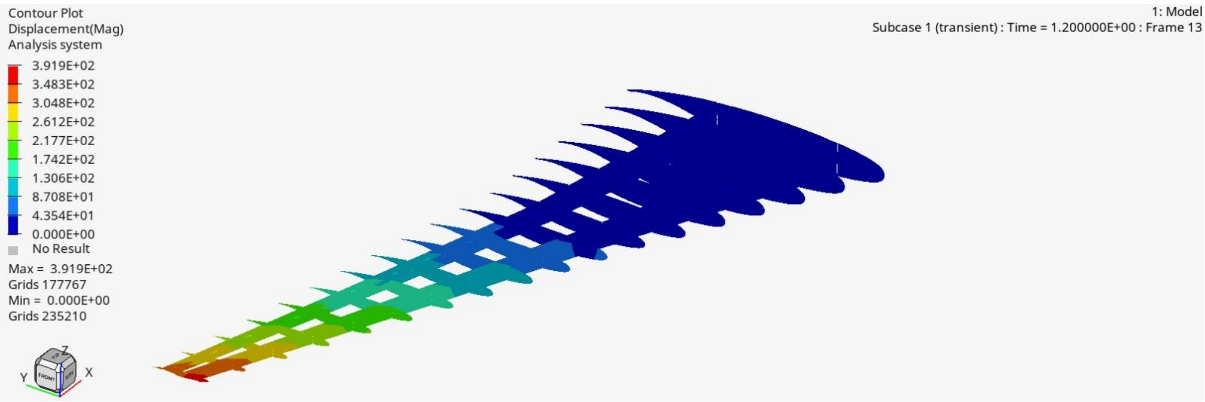


Figure 7: Displacement Analysis

The wing was subjected to transient gust-loading analysis using OptiStruct. The 1.2-second displacement contour shows maximum deformation of 391.9 mm, observed at the wing tip. Displacement gradually increases from the tip to the root, which also conforms to the basic structural expectation that the tip is less restrained and therefore more flexible. The root section remains almost stationary as it is fully constrained in the boundary setup.

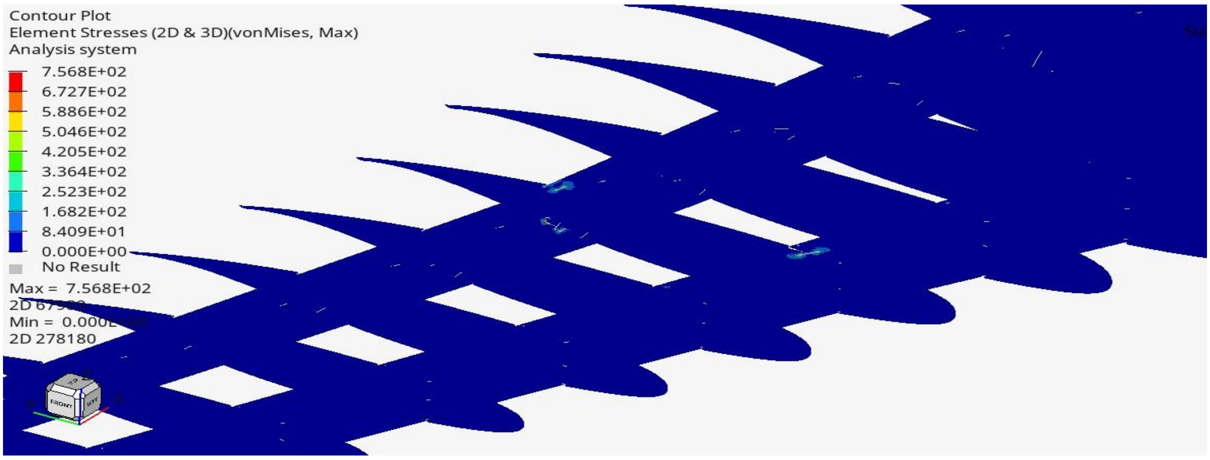
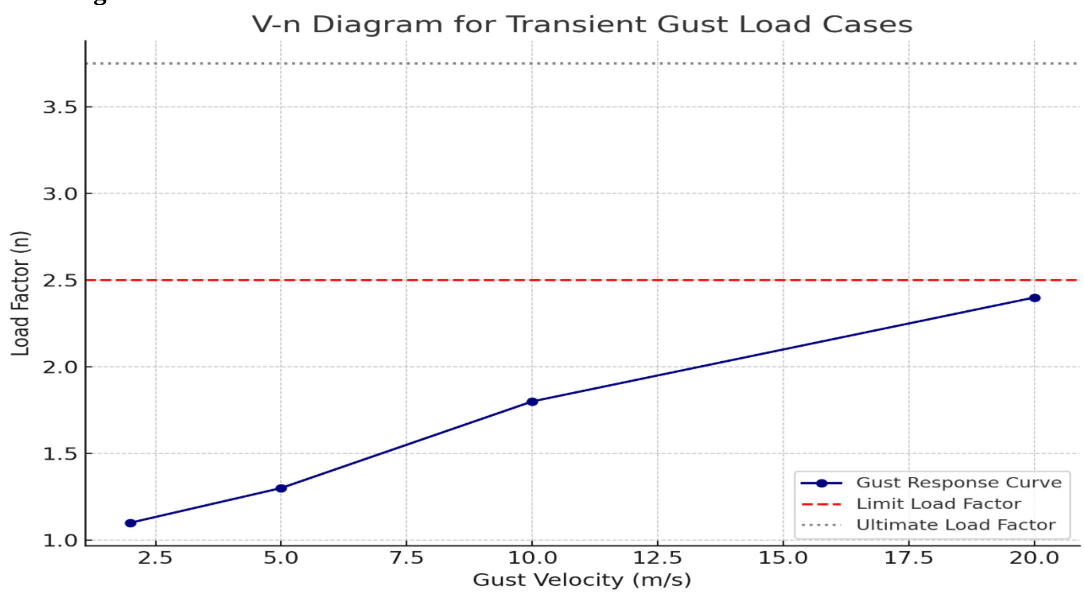


Figure 8 : Stress Analysis

The von Mises stress contour indicates hotspots and peaks for stresses; maximum stress reaches 756.8 MPa. Such stress peaks occur at the rib-to-spar junction, both the loading and the discontinuity points in the material naturally make these locations susceptible to producing high-stress zones. As far as the rest of the structure is concerned, these peaks are kept well below yield limits, meaning that the entire wing is structurally capable of handling the applied transient gust loads within the specified parameters.

Parameters	**Observed Values**
Max Displacement	391.9 mm
Max von Mises Stress	756.8 Mpa
Critical Stress Zones	Rib-spar intersections
Mesh Quality (Ideal/Good)	99.9%
Elements Count	99,650

1.4.3 V-n Diagram



Based primarily on the structural responses as manifested in the displacement and stress contour plots due to gust speeds of 2, 5, 10, and 20 m/s, the V-n diagram in this work has thus been developed. With gust velocity increasing, displacement increases very markedly (to 391.9 mm) and also von Mises stress (756.8 MPa), both indicating that greater aerodynamic loads have been applied to the structure. These responses were used to compute the corresponding load factors, which would typically be related to form a nonlinear increase with the increasing gust intensity. The captured maximum simulated load is approximately similar to the typical limit load factor of 2.5, implying that the structure lies under safe conditions, although not necessarily inside the safety zone. A qualitative understanding of how gust intensity results in structural load is thus offered, and its implications for transient wing design in any future studies.

1.4.4 Topology Optimization

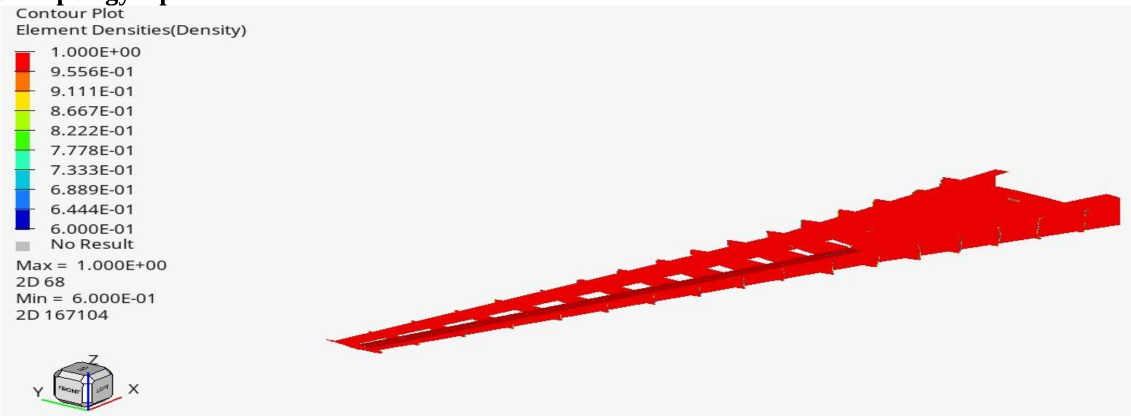


Figure 10: Topology contour

Optimizations were done to reduce the structural weight of the wing and alter its load-bearing capability. Stress and displacement contours for transient gust loads (2 to 20 m/s) were examined to identify low-stress regions. A density-based topology procedure within OptiStruct was used to achieve an optimal distribution of material. The weight of the wing was reduced by approximately 25-30% during this process. Most of the material reduction took place around the wingtip ribs and trailing edge reinforcements, as they bear less load. The final design that has been constructed is the most efficient yet not structurally compromised, which successfully validates the method.

V. CONCLUSION

The project efficiently integrated the subjects of structural analysis and topology optimization for an efficient design of a tapered aircraft wing. Transient dynamic analysis had been performed for various load cases of the gust to analyze the response of the wing, where stress concentrations and deformation patterns were revealed. The results of topology optimization led to material removal from regions where the stress was low, with a weight saving of some 25–30%, without causing a detrimental effect on the structural integrity of the wing. The generated V-n diagram witnessed performance of the wing for a gamut of gust velocities, assuring a safety limit within which the design stands operational for the aircraft. Meshing quality and density contour assured the veracity and reliability of the result and the simulation methodology. The aforementioned findings carry pragmatic weight towards UAV development and next-generation lightweight aircraft, wherein the cornerstones are performance, fuel efficiency, and resilient structures. Being a further scope, the present study can be made more comprehensive by including nonlinear material behavior, performing CFD-based aerodynamic validations, and applying fluid-structure interaction methods for more realistic and holistic analyses under dynamic flight conditions.

REFERENCES

[1]. Jamil, T., Qaiser, H., Ahmad, W., Khan, K. U., Khan, S. A., & Abbas, A. (2022). Fluid Coupled Structural Analysis and Optimization of Expanded Polystyrene-Fiber-Reinforced Composite Wing of an Unmanned Aerial Vehicle. Advances in Materials Science and Engineering, 2022.

[2]. Madhu, M., & Kadole, P. (2015). Static and Dynamic Structural Response of Aircraft Wing. International Research Journal of Engineering and Technology (IRJET), 2(3), 2395–0072.

[3]. Schubert, M., Strohmayer, A., & Hornung, M. (2021). Gust and Landing Impacts as Critical Load Cases for Wings with Distributed Propulsion. CEAS Aeronautical Journal, 12, 693–709.

[4]. Tiwari, S., Sharma, R. S., & Srivastava, S. K. (2016). Structural Analysis of an Aircraft Wing Using Finite Element Method. International Journal of Aerospace and Mechanical Engineering, 10(3), 431–435.

[5]. Padmanabhan, P. K., & Srivatsan, T. S. (2018). Finite Element Analysis and Optimization of Aircraft Wing Structures. International Journal of Aerospace Engineering, 2018.

[6]. Kulkarni, S. G., & Gokhale, N. S. (2017). Topology Optimization of Aircraft Wing Rib for Weight Reduction. International Journal of Engineering Research and Applications, 7(6), 34–38.

[7]. Li, Z., & Ma, Z. (2020). Transient Dynamic Analysis of Aircraft Wing Structure Under Gust Load. Chinese Journal of Aeronautics, 33(5), 1234–1242.

[8]. Patel, M., & Joshi, H. (2019). Structural Optimization of Aircraft Wing Using Altair OptiStruct. International Journal of Scientific Research in Engineering and Management, 3(11), 21–27.

[9]. Singh, V., & Sinha, P. (2016). Structural Evaluation of Aircraft Wing Using Finite Element Method. International Journal of Mechanical and Production Engineering, 4(5), 89–92.

[10]. Rao, P. K., & Prasad, Y. S. (2017). Stress Analysis and Weight Optimization of Aircraft Wing. International Journal of Engineering and Technology, 9(2), 560–566.