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Gaziantep University

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INVESTIGATION OF CROSSWIND EFFECT ON FLUTTER

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ABSTRACT

INVESTIGATION OF CROSSWIND EFFECT ON FLUTTER

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Crosswinds can pose danger in many situations. They can be quite dangerous on descents when they are strong. They can cause landings to cancel due to their effects on the wings of the aircraft in the horizontal and vertical planes. To elude these dangers and provide a base ground study towards future optimization studies, a chronological literature survey has been conducted and basic flutter analysis of a generic aircraft rudder has been completed using the program ANSYS which uses Doublet-Lattice method evaluate modal analysis of flutter. It is found that the most of the study about flutter has been carried out in the horizontal plane. Upon completing the aeroelastic analysis of the generic training aircraft rudder, flutter occurrence has been detected when the maximum landing crosswind limit that was set by the FAA was surpassed by 30%.

Key Words: Crosswind, Vertical Stabilizer, Aeroelastic Flutter, Vibration, Fluid Structure Interaction.

ÖZET

YAN RÜZGARLARIN ÇIRPINTI ÜZERİNDEKİ ETKİSİNİN İNCELENMESİ

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Yüksek Lisans Tezi, Uçak ve Uzay Mühendisliği
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Yan rüzgarlar birçok durumda tehlike oluşturabilir. Güçlü olduklarında inişlerde oldukça tehlikeli olabilirler. Yatay ve dikey düzlemlerde uçağın kanatlarına etki ederek inişlerin iptal olmasına neden olabilirler. Bu tehlikelerden kaçınmak ve gelecekteki optimizasyon çalışmalarına yönelik bir temel zemin çalışması sağlamak için, kronolojik bir literatür araştırması yapılmış ve dalgalanmanın modal analizini değerlendiren Doublet-Lattice yöntemini kullanan ANSYS programı kullanılarak jenerik bir uçak dümeninin temel çırpıntı analizi tamamlanmıştır. Çırpıntı ile ilgili çalışmaların çoğunun yatay düzlemde yapıldığı tespit edilmiştir. Genel eğitim uçağı dümeninin aeroelastik analizi tamamlandıktan sonra, FAA tarafından belirlenen maksimum iniş yan rüzgâr limiti %30 aşıldığında çarpıntı oluşumu tespit edilmiştir.

Anahtar Kelimeler: Yan Rüzgâr, Dikey Dengeleyici, Aeroelastik Çırpıntı, Titreşim, Akışkan Yapı Etkileşimi.

''Dedicated to my family''

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LIST OF SYMBOLS

m	Mass of the wing per unit length
L	Lift
M	Aerodynamic moment
k	Torsional spring rigidity
I	Mass moment of inertia
x	Static unbalance
$\boldsymbol{a}$	Elastic axis location
T	Pitching moment
kh	linear spring rigidity

LIST OFABBREVIATIONS

2D	Two-dimensional
3D	Three-dimensional
AGARD	Advisory Group for Aerospace Research and Development
FEM	Finite Element Model
FEA	Finite Element Analysis
CAD	Computer Aided Design
DTM	Differential Transformation Method
UAV	Unmanned aerial vehicle
DOF	Degree of freedom
NASA	National Aeronautics and Space Administration
FAA	Federal Aviation Administration
LCO	Limit cycle oscillations
CFD	Computational Fluid Dynamics
1D CUF	One-dimensional Carrera Unified Formulation
DLM	Doublet-Lattice Method

CHAPTER I

INTRODUCTION

1.1 General Introduction

Flutter is directly linked to aeroelasticity. Aeroelasticity consists of interaction of aerodynamic, elastic and inertial forces on aerospace structures. When aerodynamic interaction between fluid and structure is investigated, flutter could be observed as a result of this interaction. An interaction between the air vehicle and crosswinds can be considered as one of those aerodynamic interactions, as they can cause the fluttering effect of oscillations on the structure when strong enough.

When met with crosswind at a level strong enough to cause flutter, the consequences can be dire. Due to the possible force exertion by the crosswinds on the vertical tail wing of the aircraft, an occurring fluttering effect on the vertical stabilizer can create difficult obstacles in the control of the aircraft, as well as a rotational effect that can cause a crash if the pilot does not possess exceptional skills and reflexes.

To prevent such catastrophic results, certain steps should be followed when producing and designing such air vehicles that will come across these situations. And for that aeroelasticity is essential to be considered during the design of aerospace structures.

1.2 Research Objectives and Tasks

Aircraft structure designing processes require multidisciplinary optimization and analysis, one of the most important is the studies on Fluid Structure Interaction (FSI) and Aeroelasticity is an example of this.

Providing the findings from this investigation, this study aims to help the environment to focus attention to the flutter caused on the vertical plane of aircraft rudders during descent by strong cross winds as it results in an unbalance that threatens the safety of the landing. Also, this exerted force can result in fatigue and material defection thabrings higher costs in repair or possibility of an unexpected failure during future flights. So, this study points out a topic that is important for the aircrafts' general integrity along the descent on strong winds.

1.3 Layout of Thesis

Second chapter of this thesis begins with an extended chronological literature review about the history of flutter and aeroelasticity studies in various fields has been conducted.

Moving on to Chapter three, fundamental knowledge about aeroelasticity and theory of flutter are shared and then the solution approach the doublet lattice method is explained due to its usage during this study.

In Chapter four, generation of the generic rudder model based on the general geometries of the flight training aircrafts has been presented along with its comparison to real life models of rudder.

With Chapter five, completion of a basic aeroelastic analysis procedure of this generic training aircraft wing during various strengths of crosswinds has been demonstrated with the verifying method of mesh accuracy.

Finally in Chapter six, conclusions about this study have been revealed and predictions and recommendations have been presented for future work in this area.

CHAPTER II

LITERATURE REVIEW

2.1 Review of Flutter Studies and the relation of Crosswinds on Aircraft Wing Flutter

To have a summarized knowledge of narrowed collection of the studies that are made in the area of flutter caused by fluid structure interaction this review has been conducted. Its purpose is to illuminate the way of those who want to research further in the area and provide them the fundamental and necessary sources to help them improve the study and avoid repetition. It is important to have such guide to carry out studies and researches efficiently as it provides guide line to follow and base theory to build up on top.

To the extent of this review, the studies have been carried out since 1955 to present day in the field of flutter has been collected. As we take a look at these studies throughout years, we get to observe the different methods and materials that have been used to complete these studies in the area of flutter in different fields, such as civil engineering in bridge constructions and material engineering and mechanical engineering in composite material testing and producing and aeronautical and aerospace engineering in aircraft and wing design. In order to realize the developments and changes in the studies in the area it has been decided to have the review in a chronological order.

Table 2. 1 Wing flutter studies.

Title and Purpose of the Studies	Year	Reference
This Study’s purpose is to analyze the aerodynamic forces acting on an oscillating wing in a supersonic flow using box approach	1955	[1]
Using a program to investigate the effect of filament orientation on a swept wings flutter behavior of a subsonic aircraft	1974	[2]
Analyses of nonlinear transonic flutter are performed using a numerical method.	1982	[3]
In this study time-marching transonic flutter solutions are studied with the inclusion of the effects that caused by the angle-of-attack	1983	[4]
Aerodynamic forces were employed in a flutter analysis to evaluate the relationship between flutter speed and amplitude. This adaptation of the descriptive function technique is special in that it considers the primary harmonic of the nonlinear oscillatory motion.	1984	[5]
Using the Unsteady Euler Aerodynamic Method, wing flutter boundary prediction was developed.	1995	[6]
The effects of nonlinear aerodynamics on the divergence, flutter, and limit-cycle oscillation properties of a transonic airfoil configuration was investigated	2002	[7]
A full-scale test was conducted to identify the structure's key areas upon failure so the strain data could be determined and the wing's fatigue life could be confirmed	2018	[8]

Table 2. 2 Various flutter studies.

Title and Purpose of the Studies	Year	Reference
A review was made to mark the advances in the Flutter analysis and predictions in the structures of fans and compressor blades which are strongly influenced by the effects of flutter	1975	[9]
Flutter analysis of large dynamic systems with numerous structural nonlinearities is provided using an iterative frequency domain approach	1986	[10]
Using the Euler Equations, a flutter analysis of the transonic interval was performed.	1987	[11]
Upon the conclusion of this study for robust flutter analysis, match-point solutions were provided	2002	[12]
This article presents a flexible uncertainty description for unstable aerodynamic forces using the μ-k method when solving for robust flutter	2004	[13]
A computation was done for the aerodynamic damping outcomes of its flutter analysis for a fan operating in the transonic region.	2011	[14]

Table 2. 3 Aircraft flutter studies.

Title and Purpose of the Studies	Year	Reference
This study aimed to find out the effect of structural non-linearities upon aircraft during its vibration and flutter caused by aerodynamic and mechanical forces	1978	[15]
Modern methods are used such as computational fluid dynamics for wing flutter analysis.	1988	[16]
The CF-18 aircraft's flutter characteristics with structural nonlinearities that are caused by flutter were studied using the method of describing function	1989	[17]
A complex notation in flutter analysis was provided	1998	[18]
Upon the flutter of a high-performance aircraft, an aerodynamic prediction in an unsteady state was offered	2003	[19]
A flutter analysis was provided in a state of an aircraft with both a swept wing and a powered engine	2010	[20]
Investigation Into Gust Load Alleviation Using Computational Fluid Dynamics This paper shows the first results of applying higher-fidelity aerodynamics in the design of a basic gust controller to mitigate gust-induced loads using traditional aerodynamic modeling approaches	2019	[21]
A methodology for probabilistic analysis is created using the bimodal coupled flutter of the two degree of freedom ridge section as an example and validation with experimental data	2020	[22]

Table 2. 4 Bridge flutter studies.

Title and Purpose of the Studies	Year	Reference
For use in the construction of suspension bridge crossings, a computer method for forecasting flutter speeds has been devised	1988	[23]
Using a developed modal technique, an aerodynamic flutter analysis was completed on bridges of suspension	1989	[24]
For bridges with their suspension provided by cables, an aeroelasticity analysis was carried out using the finite-element method. A method that its generality permits more flutter scenarios to be examined in different fields.	1992	[25]
Flutter Stabilization and Heaving-Branch Flutter The goal of this research is to explain how super-long span bridges flutter	1999	[26]
For forecasting the coupled flutter and response of buffeting from long span bridges, the authors offer a time domain technique.	2000	[27]

Table 2. 5 Composite plate flutter studies.

Title and Purpose of the Studies	Year	Reference
A flutter analysis is made to investigate the behavior of a cantilever composite plate that is affected by subsonic flow.	1989	[28]
Benefiting from the shear deformable finite elements a supersonic case of flutter analysis was conducted upon symmetrically clamped composite panels	1991	[29]
A high-precision thin shell finite element is used to explore the flutter behavior of laminated composite plates and shells in a supersonic case.	1993	[30]
Using finite elements, an analysis of fluttering effect was completed over panels consisting of laminated composite materials	1994	[31]
Using finite elements, an analysis of fluttering effect was completed over panels consisting of skew composite materials	1996	[32]
The impact of altering fiber spacing on supersonic flutter of rectangular composite plates was investigated using the finite element method and quasi-steady aerodynamic theory.	2011	[33]
In a supersonic case of flutter of a plate consisting of composite laminate an active aeroelastic analysis was performed and the vibration of it were controlled	2012	[34]
An innovative aeroelastic formula founded on doublet lattice, g-method, and higher-order one-dimensional structural models was used to calculate the flutter conditions.	2013	[35]

Table 2. 5 Continued

A theory of shear deformation of inverse trigonometry was provided about the characteristics of a multilayered plates consisting of composite materials in a supersonic case of flutter	2016	[36]

Table 2. 6 Rudder flutter studies.

Title and Purpose of the Studies	Year	Reference
Flutter Calculation and Analysis of Rudder System Based on a binary wing linear flutter model, the flutter law of a linear rudder system is derived and studied in this study	2016	[37]
Simulating a flutter analysis of the vertical stabilizer in a high-speed air vehicle this study provides extensive data showing the aeroelastic characteristic of a control rudder. The study suggests a unique parameter-tuning strategy for optimizing the vertical stabilizer's flutter characteristics once the simulation is complete.	2018	[38]
In a study focusing on an investigation of methods of aeroelastic analysis for three-dimensional vertical stabilizer. It aims to provide accurate results in analyzing the structure in the case of a transonic flow for high-speed air vehicles.	2021	[39]

2.2 Materials and Methods in the Review

In the review, certain keywords were searched in the database on the basis of title and full paper. As a result of the literature review, it was seen that qualitative, quantitative and mixed research methods were used in 40 conceptual and applied studies. In the study carried out within the scope of literature analysis, the databases used (Elsevier, Research Gate, Science Direct and Google Scholar) were scanned with the keywords "flutter" at the "Title" level in the first stage of the study, and 45 articles were examined. In the second stage, 72 articles were chosen at the "Whole Text" level with the keywords "Composite flutter, aircraft flutter, bridge flutter, Aeroelastic flutter, Cfd flutter". At the last stage, a total of 4 articles directly related to the subject were identified and scanned based on the "Rudder Flutter" criterion. All of the articles within the scope of the evaluation are international publications.

2.3 Flutter Studies

2.3.1 Horizontal Wing Flutter Studies

Beginning the review with a method called box approach that has been developed to analyze the forces acting on an oscillating wing that is in a supersonic flow in 1955. It entails creating a grid of square boxes to mimic the wing and determining the influence of each box on the others. A routine flutter analysis of a wing with arbitrary chosen normal modes can be performed. The box approach looks to provide a straightforward routine for assessing wings with flexibility for supersonic flutter investigations that is well suited to computer programming. Without further adjustment, the square box approach presented here for subsonic edges is not applicable to Mach numbers below M = 1.414. [1]

Coming to the year of 1974 a flutter analysis of airplanes with flexible fuselages and engines mounted on flexible pylons was done using a computer software. This program has been used in parameter studies to investigate the filament orientations effect on wings fluttering behavior. The flutter determinant is calculated using finite differences, and the root locus branches with the lowest flutter speed are found. As the parameters are changed, the programs design is to detect sudden changes in the lowest possible flutter speed and mode shape. [2]

As of 80s, A nonlinear transonic flutter analysis is carried out with a numerical approach. The approach can forecast the nonlinear interplay between unstable shock wave movements and an elastic wing's dynamic response. The existence of the "transonic bucket" is indicated by computed results. However, in order to be regarded feasible for further investigation, the method requires a more complete validation than the preliminary results reported here. [3]

For a time-marching transonic flutter solutions are studied with the inclusion of the effects of angle of attack. Using the transonic small perturbation potential equation aeroelastic solutions are studied. A complicated exponential modal identification technique is used to study time-marching transient solutions of both plunging and pitching airfoils. For the MBB A-3 and NACA 64A010 airfoils, the code HYTRAN2 is utilized to determine the boundaries of transonic flutter vs. Mach number and angle of attack. The MBB Airfoil is able to have different flutter speeds at a given Mach number when the influence of static pitching moment on the angle of attacks is taken into account. [4]

Moving on to a flutter analysis using aerodynamic forces a unique modification of the descriptive function approach that takes the first fundamental harmonic of the nonlinear oscillatory motion into consideration is used to determine the flutter speed dependency on amplitude. It is also mentioned in this study that the flutter analysis methods that are traditionally used can still be employed if the aerodynamic nonlinearities effects are included in. For a NACA 64A006 airfoil with Mx = 0.86, the aerodynamic forces are estimated using the LTRAN2 aerodynamic algorithm. [5]

Using unsteady Euler Aerodynamic method, a prediction of wing flutter boundary is made. Experimental data for seven freestream Mach values are compared to results of Euler flutter for an isolated 45' swept back wing over a range of flutter boundaries from 0.499 to 1.14. In comparison to the experimental boundary, aeroelastic results that are computed anticipate a premature rise in the flutter border. The essential flow properties of the time-marching flutter calculations are illustrated using steady and unsteady contours of surface Mach number and pressure. [6]

The effects of nonlinear aerodynamics on the divergence, flutter, and limit-cycle oscillation (LCO) properties of an airfoil configuration in a transonic state is investigated. To describe stable and unsteady transonic flows, a cutting-edge computational fluid dynamic (CFD) approach is applied. For the one and two DOF flutter models, nonlinear aerodynamic effects create a positive transonic divergence trend as well as unstable and stable LCO solutions, respectively. Based on unsteady-dynamics offered by a frequency-domain harmonic balancing solution for the nonlinear CFD model, a new LCO solution technique is created to determine the LCO response. For the same transonic airfoil, this approach has found both stable and unstable LCO responses. The new LCA solution approach, along with the aerodynamic harmonic balance method, could prove to be a useful tool for analyzing LCO behavior. [7]

The test was carried out to identify the structure's key areas, determine strain data, and confirm the wing's fatigue life. Regular NDI inspections and crack growth monitoring are required to guarantee that faults are found and fixed before they reach critical magnitude, as the integrity of the aircraft structure is based on regulated crack growth. Some failures are repairable, while others necessitate the reconstruction of the crucial component or the substitution of new components. [8]

2.3.2 Various Flutter Studies

Every span wise location on each blade requires an accurate prediction of vibrational deflections and unstable aerodynamic forces. The work done by the air on the blades will balance the work dissipated by friction and material dampening in neutrally stable systems. Aerodynamic damping calculations necessitate a precise forecast of vibration displacements and unstable aerodynamic forces. Aerodynamic damping has been proven to be much higher than mechanical damping and to be strongly dependent on air-density. It is recommended to configure the aerodynamics damping to be positive over the whole compressor working map for engines that must operate over a large inlet pressure range. [9]

Later in the 80s this iterative procedure for the nonlinear flutter analysis has been developed. Before the final stability characteristics are computed, the approach is used to get the oscillation amplitude in each nonlinear spring and the describing function prediction of stiffness aligned. As a result, the system is tuned to the flutter frequency when the system is unstable. The technique accurately predicts the magnitude of a limit cycle flutter aside of the initial disturbance required to cause flutter in the circumstances analyzed. [10]

Using the Euler-Equations a transonic flutter case is analyzed. In the investigation of a transonic flutter of typical section wing models by a solution of the Euler equations on a moving mesh the unsteady aerodynamic loads are obtained. It is found that the determination of Aeroelastic stability happens by the integration of the coupled equations of motion for the fluid and structure forward in time. [11]

In terms of potential modeling flaws, robust flutter speeds indicate the worst-case scenario. Speeds of flutter can be calculated using a previously provided model formulation. The solution can take into account parametric uncertainty in all the elements, where the prior formulation didn't take mass uncertainty into account. The right treatment of nonlinear uncertainties and perturbations results in the match-point nature of this formulation. Since of the subsystem approach, this formulation is advantageous because it allows elements of the model to be quickly altered without arduous algebraic labor. For both nominal and robust flutter speeds, the technique analysis computes match-points solutions. [12]

Further studies present a flexible uncertainty description for unstable aerodynamic forces. The description is applicable to all frequency-domain aerodynamic approach that has the same level of geometric information as the underlying aerodynamic model. In low-speed airflow, the presented method is applied to a wind-tunnel model. Then, using structured singular value analysis, an explicit criterion for robust flutter stability is derived. The approach for computing a worst-case flutter boundary that results is similar to a p-k or g-method flutter analysis. Finally, the presented method is applied to a low-speed airflow wind tunnel model with success. [13]

An aerodynamic damping’s computational analysis to predict flutter characteristics of a transonic fan stage with a highly loaded rotor and a tandem stator is described in a publication. TRACE, is used to analyze the fan's flutter stability numerically. The geometry of the blade mode is a critical component to determine the stability. The shock movement and location, as well as their relationship to the inter blade phase angle, all have a role in the aerodynamic damping variation. This relationship's precise nature necessitates further investigation. [14]

2.3.3 Aircraft Flutter Studies

In the year of 1978 this project is carried out to determine the physical causes of various forms of non-linearities, analyze their impact on various aspects of the flutter clearing process, and deal with methodologies that allow for quantitative solutions to aeroelastic issues to find out what effects the structural non-linearities has on the aircraft vibration and flutter. [15]

Modern methods are used such as computational fluid dynamics for wing flutter analysis. The application and evaluation of the CAP-TSD transonic small disturbance code for flutter prediction are presented in this work. This code was developed for the aeroelastic analysis of whole aircraft designs, and it has been used to compute stable and unsteady pressures with success. For various supersonic and subsonic freestream Mach values, the flutter limits from CAP-TSD (linear) and compared well with experimental flutter data. In order to validate this code for all transonic aeroelastic applications, this was the first step. [16]

Flutter characteristics with structural nonlinearities for the CF-18 aircraft are studied using the describing function method. According to the flutter sensitivity research, limit-cycle flutter of the wing rotation and outer wing rotation modes assumes the function of divergent flutter involving the wing bending and torsion modes. Limit-cycle oscillations are only possible within a very narrow range of velocities, around the linear flutter velocity. Limit-cycle flutter at the wing-fold is shown to be lessened by positive aileron angles than by negative angles. Similar observations are obtained at the outboard leading-edge flap hinge. The describing-function approach can be used to accurately analyze the CF-18 aircraft's flutter characteristics. [17]

In late 90s a complex notation for flutter analysis is studied. Motion-induced aerodynamic forces must be included in flutter analysis in aircraft or bridge engineering. These forces can be expressed mathematically in two ways: as real number or complex number representations. Using either type of notation appears to be a matter of personal preference, as both produce identical numerical values. The application of real and complex numbers in flutter analysis has been investigated. It has been discovered that complicated notation equations for motion-induced aerodynamic forces are more compact. They are quite simple to include into the framework of structural dynamics from an instructional approach. The use of complex notation results in a compact and elegant eigenvalue problem that is simple to solve. However, this results in a less handy form that necessitates more computational effort to solve. [18]

For subsonic assessments of flutter studies of high-performance military aircraft in production, the doublet-lattice method was still the most popular option. For this speed range, ZONA codes appear to have achieved significant recognition. The ideal characteristics of any unstable aerodynamics code were highlighted, and a forecast of CFD code development was offered. [19]

Here besides the effect of the wind, the effect of a powered engine is taken into consideration. It is presented how flutter occurs in powered aircraft with swept wings. To properly account for the location and features of the engine mass and thrust force, Heaviside and Dirac delta formulas are used. The Galerkin technique is then used to convert the partial differential equations into ordinary differential equations. To better understand the effects of wing sweep angle, thrust value, engine mass, and location on wing flutter speed and frequency, numerical simulations of an F1 engine's stability domain were run. It was discovered that the location, mass, and thrust magnitude of the engine have a significant impact on the instability domain. [20]

Gust load sizing is an important aspect of aircraft design. A paper shows the first results of applying higher-fidelity aerodynamics in the design of a basic gust controller to mitigate gust-induced loads using traditional aerodynamic modeling approaches. Near transonic cruise conditions, results are reported for both an aerofoil and a big aircraft layout. Following a demonstration for a transonic aerofoil case, the techniques are successfully used on a big civil aircraft that is almost ready for production. Overall, it is anticipated that the design of present control laws based on linear-potential aerodynamic theory can be easily improved by employing comparable computational fluid dynamics techniques. [21]

Using the bimodal coupled flutter of two degree of freedom ridge section for illustration and validation using the example's experimental results, a probabilistic analytical framework is created and it is concluded that there is a possibility of accuracy and efficiency being retained. [22]

2.3.4 Bridge Flutter Studies

The rate at which completed bridges flutter is determined by its natural frequencies in vertical flexure and torsion, as well as the geometry of the deck section. For use in the construction of suspension bridge crossings, a computer method for forecasting flutter speeds has been devised. Numerical integration of the equations of motion of a 3-D suspension bridge model has been used to demonstrate that approaches that consider the problem as solely two dimensional may have inherent conservatism. [23]

Moving on, an aerodynamic flutter of a suspension bridge is made using a modal technique. In an interaction analysis, the aerodynamic forces are combined with the lowest vertical and torsional natural mode forms. When one of the complex eigenvalue pairs has a zero real portion and a non-zero imaginary part at a certain wind speed, flutter instability is suggested. [24]

The pK-F approach has proven to be both dependable in terms of methodology and effective in terms of application. The entire method is provided as a matrix, making it simple to include into finite element systems. In terms of solution technique and execution effectiveness, the developed pK-F method for flutter analysis of bridges with cable-suspension has shown to be dependable. By using this technique, bridge designers are able to control damping- and stiffness-driven flutter using a single algorithm. The method's extensibility enables more flutter scenarios to be investigated, such as distinct flutter derivatives for various bridge structure components and different building stages. [25]

To explain how super-long span bridges flutter research has been made. Numerous wind tunnel tests are performed on the basic girder sections, including the flat diamond section, twin rectangular cylinder, and rectangular cylinder. The first two sections show that, in comparison to traditional linked flutter, the torsional branch has very stable aerodynamic features. The flow separations at two separate positions on the body's side-surface are the main cause of flutter stabilization in flat diamond sections. The opening space and turbulent flow created in the upstream side of a dual rectangular cylinder contribute significantly to the flutter characteristics. [26]

In the early 2000s studies about flutter has become more advanced as the researchers in this area increased with the need for optimization problems in order to catch up with the needs of exponentially advancing technology. This study looks into the time domain flutter of bridges and their response of buffeting. For predicting the coupled flutter and buffeting response of long span bridges, the authors offer a time domain technique. To represent frequency dependent unstable aerodynamic forces, convolution integrals with the aerodynamic impulse function and structural motions or wind fluctuations are utilized. The response analysis can model the nonlinearities of both aerodynamic and structural causes. The experimentally recorded flutter derivatives, the aerodynamic admittance functions, and the spanwise coherence of the aerodynamic forces are used to produce the aerodynamic impulse functions using rational function approximations. The frequency dependent properties of unstable aerodynamics may be modeled in the response analysis, which is a key component of the approach provided here. [27]

2.3.5 Composite Plate Flutter Studies

A composite material consisting cantilever plate's behavior in subsonic flow is examined using a flutter analysis. A finite element method of high-precision 18-degree-of-freedom triangular plate-bending is used to examine the effects of composite filament angle, sweep angle, orthotropic modulus ratio and aspect ratio on the vibration and characteristics of cantilever plates in the case of a subsonic flow resulting in flutter. The traditional lamination theory is used to create the stiffness and mass matrices of the elements. [28]

In 90s an analysis is carried out about the composite panels under supersonic flutter conditions using shear deformable finite elements method. The flutter of panels consisting of composite materials in supersonic cases of flow was examined using the finite element approach, which is based on the first-order shear deformable theory. It has been discovered that composite plates made of cross-ply and angle-ply both have flutter boundaries. The flutter boundaries are highly influenced by the plate aspect ratio, flow direction, and fiber orientation. The flutter dynamic pressure reaches its maximum value for both rectangular and trapezoidal plates close to the value $ = 0. In laminated plates with clamped edges, panel shape, length ratio, flow direction, and fiber orientation all have a significant impact on the flutter boundaries. [29]

A finite element of high-precision doubly curved quadrilateral thin shell is used to explore the behavior of plates and shells consisting of laminated composite in the case of supersonic flutter. The accuracy, effectiveness, and practicality of the modern finite element approach are illustrated with examples. For a selection of selected scenarios, parametric evaluations of the impacts of boundary conditions, degree of orthotropy, fiber orientation, and flow angle on the flutter characteristics are demonstrated. The findings of this study are expected to be beneficial in determining the effects of angle of attack and aerodynamic heating on a real-world panel flutter system. They will specifically aid in the demonstration of the applicability of the current curved quadrilateral thin shell finite elements to such a system. [30]

Understanding the aeroelastic behavior of cantilever panels necessitates a comprehensive examination of many composite characteristics. The flutter parameter is destabilized by the coupling caused by anisotropy and lamination. Flutter resistance was higher in panels with stronger boundary restrictions. [31]

Another example of a finite element method on flutter analysis for composite panels. Using eight-nod iso-parametric elements, the finite-elements approach accounts for transverse shear deformation. For various aspect ratios, boundary limitations, fiber orientations, and lamination methods, the impact of skew angle on crucial aerodynamic characteristics are explored. The conventional finite element formulation for rectangular planforms was altered by the application of skew boundary constraints in order to examine the effects of skew angle on the flutter behavior of both unidirectional and laminated composite panels. The primary finding of the study is that the behavior of a certain planform is significantly influenced by the fiber angle, lamination scheme, aspect ratio, and boundary circumstances. [32]

Using the finite element approach and quasi-steady aerodynamic theory, the effect of varying fiber spacing on rectangular plates consisting of composite material in the case of supersonic flutter was examined. On the flutter boundary, the punch phenomena can be seen in the absence of aerodynamic damping. This research examines the flutter behavior of a single layer composite with varying fiber spacing.

The best composite plate design with variable fiber spacing will be an appealing topic. [33]
At the flutter limits, supersonic composite laminated plates with piezoelectric patches are examined for active aeroelastic flutter analysis and vibration control. The aerodynamic pressure is estimated using the Houbolt numerical algorithm, and the impulse responses of the structural system are calculated using supersonic piston theory. [34]

An improved aeroelastic formulation evaluated from higher-order one dimensional structural models, the doublet lattice method, and the g-method was used to determine the flutter conditions. Theories were improved using expansions similar of Taylors' e of the cross-section displacement field. The results show how CUF 1D has increased its ability to handle flutter analysis of typical composite lifting surfaces with plate-like precision and low processing costs. Thin-walled constructions' in-plane distortion can be predicted by CUF 1D with great accuracy and at a low computational cost. Future study should concentrate on the coupling of CUF 1D with fluid dynamics tools and extensions to structural non-linearities. [35]

An article examines the fluttering behavior of plates consisting of multilayered composite materials subjected to yawed supersonic flow on the flutter boundary, the punch phenomena can be seen in the absence of aerodynamic damping. by extending the theory of inverse trigonometric shear deformation. Important conclusions are obtained after investigating the effects of many parameters like lamination sequences, boundary conditions, material anisotropy, flow angles, and more. In order to improve the flutter boundary of supersonic vehicles, flow angles should be regarded as important design parameters. To investigate the free vibration and flutter behavior of isotropic and multilayered composite plates, inverse trigonometric shear deformation theory is used. An inverse cotangent function that generates a non-linear shear stress distribution is used to calculate the ITSDT. [36]

2.3.6 Rudder Flutter Studies

Finally arriving to present time studies about the rudder system has started to get focused on. Which brings us closer to investigate out issue at hand about the effect of crosswinds on the aircrafts rudder system.

Based on a binary wing linear flutter model, the flutter law of a linear rudder system is derived in a study. The hydrodynamic calculation method for two degrees of freedom binary wing in arbitrary time domain is used to model and calculate the nonlinear flutter phenomenon of the rudder system with interval. The calculations reveal that the closer the mass center is to the elastic shaft, the better the flutter velocity, and thus adding balance weight to the rudder blade is commonly utilized to advance the mass center. The smaller the dimensionless density value, the more difficult it is for flutters to develop; hence, lowering the mass of the rudder blade helps to enhance flutter velocity. At the same time, it is discovered that strengthening the rudder shaft's torsional rigidity has the same effect. [37]

The control rudder of a high-speed flight vehicle is examined in this paper for its flutter characteristics. By combining parametrized dynamic modeling technology with aerodynamic and aeroelastic flutter analysis methodologies, the paper proposes a novel parameter-tuning method for flutter characteristics optimization of the control rudder at the initial design stage of the flight vehicle. Leading edge sweep angle, tip chord length, root chord length, and span are some of the typical parameters whose impacts on the flutter characteristics of the control rudder in a high-speed flight vehicle are examined. The results have important ramifications for designing rudder configurations and may be applied to save design cycle time and eliminate design iterations. Studies using simulations show how effective the recommended approach is for controlling rudder flutter analysis. The findings serve as a useful guide for rudder structure and form optimization and modification in early high-speed aircraft design, which can successfully prevent rudder design duplication in middle and later phases. [38]

The AGARD 445.6 wing employs frequency domain flutter analysis based on three-dimensional wing rudder to deliver very effective and precise flutter analysis for high-speed aircraft in transonic flow. It is clear from the simulation findings that the flutter process in the subsonic and transonic regimes is accurate since they agree with experiment and reference data. This simulation boosts efficiency and decreases computation time while also improving the accuracy of the flutter analysis. It therefore lays the foundation for high-speed aircraft to anticipate transonic flow flutter. [39]

2.4 About Crosswind and its Effects

According to the online page regarding crosswinds and safety, how much crosswind is actually too much or not depends on your degree of experience and how much practice you receive. Almost all aircraft are equipped with a "demonstrated crosswind" feature. According to a citation, the FAA stipulates that an airplane must demonstrate its crosswind capacity to be "satisfactorily controlled with no unusual degree of skill or vigilance on the part of the pilot in 90-degree crosswinds up to a velocity equivalent to 0.2 VSO." That entails a wind speed that is at least 20% of the stalling speed of the aircraft when the engine is off and the landing gear or flaps are lowered. That doesn't mean it is not allowed to go over that limit. However, if there is more crosswind than that, it is necessary to have a more "extraordinary degree of expertise," as the FAA puts it, to safely touch down. Additionally, the plane's crosswind capabilities are far exceeded if the pilot is on final approach and unable to maintain runway alignment with full rudder. If it ever occurs, the pilot will need to choose a better runway or an alternative airport. This article mentions the incapability of the aircrafts under such circumstances. Completing this research optimization for the material and geometric structure of a designated aircraft can be made. [40]

In Chapter 9, the FAA explains the fundamentals of maximum safe crosswinds. (Approaches and landings) of the Airplane Flying Handbook. [41]

2.5 Results of the Review

Within the framework of the findings obtained as a result of the literature review, in the publications; two informative conceptual study was found and it was seen that qualitative, quantitative and mixed research methods were used in the other 39 applied studies. However, over the years, it has been observed that the studies on flutter have developed in every field and become more detailed and consistent. It has been observed that the studies carried out so far are open to development and have strong foundations in order to make our daily lives safer and more efficient in the future.

The framework for the literature review conducted by the researchers is presented in Table 1, Table 2, Table 3, Table 4, Table 5 and Table 6.the tables are determined and grouped by the flutter sub-topic studies.

CHAPTER III

THEORY OF FLUTTER

3.1 Aeroelasticity

Aeroelasticity could be investigated in two main subjects; Static Aeroelasticity and Dynamic Aeroelasticity. Static Aeroelasticity consists of; load distribution, divergence, control effectiveness, aeroelastic effect on static stability. Dynamic Aeroelasticity consists of; flutter, buffeting, dynamic response, aeroelastic effect on dynamic stability. In the case of crosswinds and its effect on vertical surfaces, flutter subject of dynamic aeroelasticity is need to be investigated.

3.1.1 Aeroelastic Stability

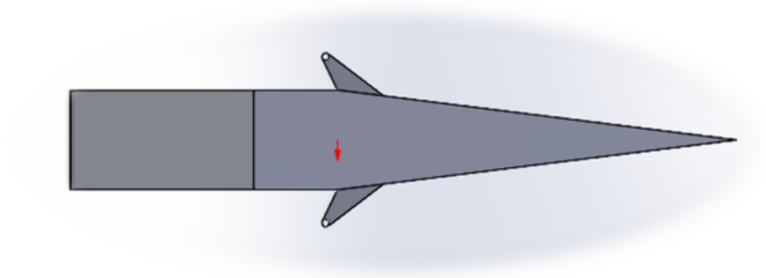

Figure 3. 1 Rudder top profile.

The following are the differential equations for the linear flutters of binary wings:

$$m\ddot{h} + mxa\ddot{\alpha} + khh = -L(t) \qquad (1)$$

$$mxa\ddot{h} + I\alpha\,\ddot{\alpha} + k\alpha\,\alpha = T\alpha\,(t) \qquad (2)$$

where m is the wing's mass, kh is its linear spring rigidity, k is its torsional spring rigidity, and h is its stiffness center's heaving displacement; L is lift, T is pitching moment, and t is time. I is the moment of inertia of the vertical stabilizer to the stiffness center per unit span. [37]

3.2 Flutter Equation Solution

In basic flutter equation solutions, there are various methods available. In generalizing them two base groups can be named; frequency domain and Laplace domain solutions.

3.2.1 The Doublet-Lattice Method

In this sub chapter the methodology used for this thesis was explained briefly. The DL-method is a lifting element technique in which the lifting surfaces are separated into trapezoidal elements that are infinitely thin (panels). These components are organized in strips that are parallel to the freestream direction. An analogous pressure jump over the surface may be compared to the distribution of acceleration potential doublets that each element possesses. Each potential (pressure jump) is focused at its 1/4-chord line (lifting line) and oscillates with strength that is unknown. Additionally, the center of each element's 3/4-chord line serves as a control point (collocation point). For each control point, the normal-wash produced by all lifting lines is added. A series of algebraic equations are produced by equating this to a specified normal-wash that is obtained from the lifting surface's oscillatory nature. These equations may be used to calculate the lifting line's strength and, consequently, the pressure jump over the surface. The local and overall aerodynamic force coefficients are obtained by surface integration.

An empirical tool that makes it easier to integrate the singular equation is the Doublet-Lattice approach. The Doublet-Lattice method's benefit is the computer program it produces, which is very simple even for complicated setups. [42]

CHAPTER IV

DESIGN MODELING

4.1 Rudder Geometry

The rudder has been generated from the geometrical references of commonly used training aircrafts rudders to have a generalized result. As the vertical stabilizers usually are, this generic training aircraft rudder was generated in a symmetrical profile.

The 3D model of the rudder was created using SOLIDWORKS based on average geometric measurements obtained by common training aircrafts.

4.1.1 Comparison of Reference Geometry and Generic Generated Rudder

FAA has similar crosswind limits for similar sized aircrafts, in order to get generalized results and avoid focusing on a certain rudder mode two different CAD models were created; one for the analysis and the other for reference due to its accurate geometry.

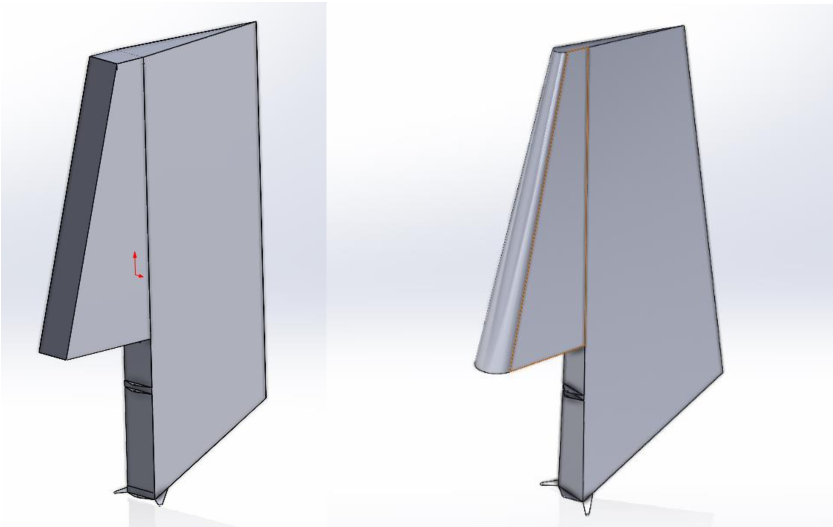

Figure 4. 1 Comparison of created models.

To have a least complex results in the analysis, instead of a tapered frame model, a parallel shaped frame model was preferred.

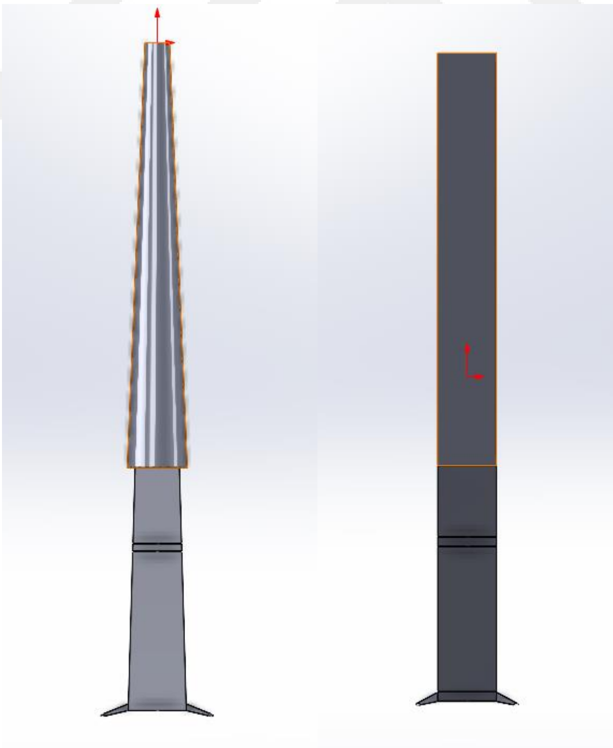

Figure 4. 2 Front view comparison.

Main reason of the choice of the sharp leading edge instead of the conventional airfoil models is to not over work the mesh model, since the analysis only focuses on the crosswinds effect and that effect only remains in one profile area.

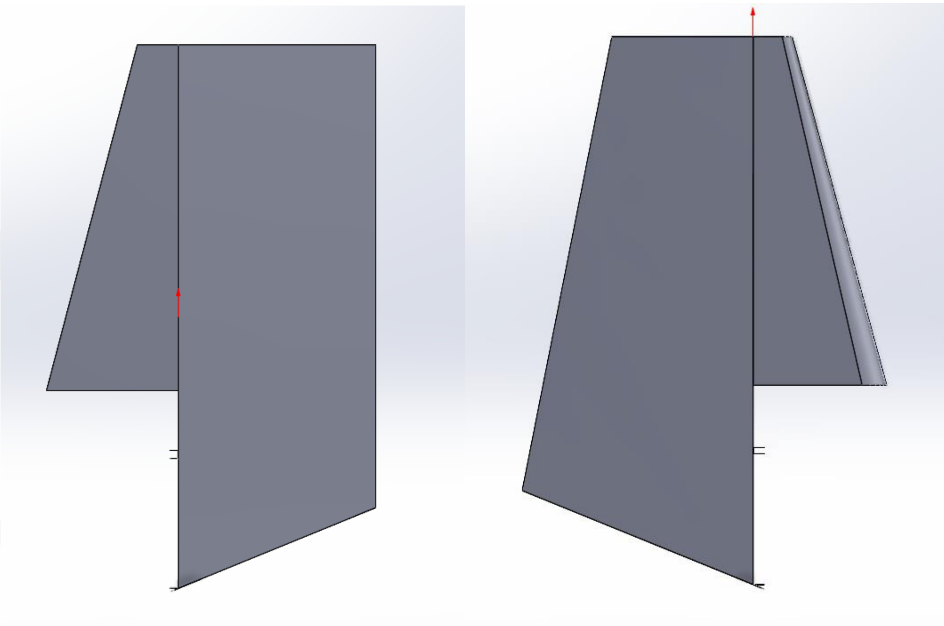

Figure 4. 3 Side view comparison.

The difference between the accurate airfoil leading edge and the generic models sharp design is more prominent in the top view comparison of models. Although this generic model is suitable for the structural and modal analysis, it might prove obsolete in the fluent analysis due to its simple aerodynamic shape.

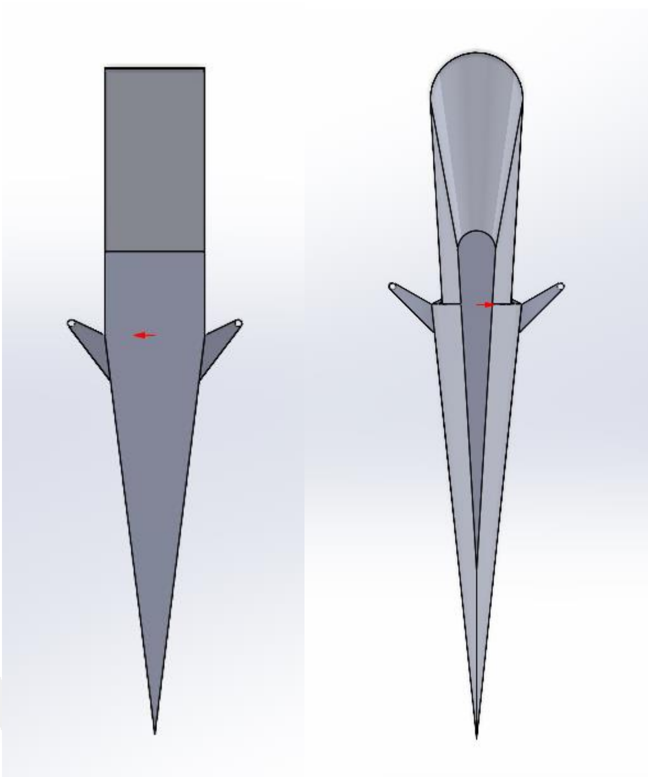

Figure 4. 4 Top view comparison.

4.2 Rudder Material

Due to its widespread use among common training aircrafts Aluminum alloy was selected to be the material of the rudder to obtain more realistic results for the training aircrafts.

Properties of selected material were transferred from the library of the analysis program ANSYS.

Table 3. 1 Mechanical properties of Aluminum alloy.

Contents of Engineering Data	Source	Description
Material		
Aluminum Alloy	Ger	General aluminum alloy. Fatigue properties come from MIL-HDBK-5H, page 3-277.

Properties of Outline Row 3: Aluminum Alloy

	A	B	C	D	E
1	Property	Value	Unit		
2	Material Field Variables	Table			
3	Density	2770	kg m^-3		
4	Isotropic Secant Coefficient of Thermal Expansion				
6	Isotropic Elasticity				
12	S-N Curve	Tabular			
16	Tensile Yield Strength	2,8E+08	Pa		
17	Compressive Yield Strength	2,8E+08	Pa		
18	Tensile Ultimate Strength	3,1E+08	Pa		
19	Compressive Ultimate Strength	0	Pa		
20	Isotropic Thermal Conductivity	Tabular			
23	Specific Heat Constant Pressure, C_p	875	J kg^-1 C^-1		
24	Isotropic Relative Permeability	1			
25	Isotropic Resistivity	Tabular			

Table 3. 2 Field variables of Aluminum alloy.

Table of Properties Row 2: Aluminum Alloy Field Variables

	A	B	C	D	E
1	Variable Name	Unit	Default Data	Lower Limit	Upper Limit
2	Temperature	C	22	Program Controlled	Program Controlled
3	R-Ratio		-1	Program Controlled	Program Controlled

CHAPTER V

AEROELASTIC ANALYSIS

5.1 Static Structural and Modal Analysis

This chapter provides some information about the process of a static structural and modal analysis on a generated rudder modal to simulate the effect of flutter due to crosswinds upon descents.

5.1.1 Calculation of the Wing load

To evaluate normal pressure to the vertical stabilizer surface caused by crosswinds, first the speed of the wind needs to be determined. Considering the landing will be on sea level where crosswinds are strongest hence the air density was taken accordingly and to reach a reliable result 2 different wind speeds within the safety limit were selected; 15 and 17 Knots. To simulate what might happen when this safety limit was to be surpassed, a wind speed that is approximately 30% above the safety limit of crosswinds upon landings were selected, which is 20 Knots

Due to the geometry of the vertical stabilizer, vectors of the crosswind need to be calculated. Dynamic pressure and the wing load were calculated upon the angle between the normal of crosswind and the surface area of the vertical stabilizer where the fluid and the structure interacts.

Table 5. 1 Cross wind and its exerted force on the surface area.

Wind Speed [Knots]	Dynamic Pressure [Pa]	Wing Load [N]
15	36,47	12,537
17	46,85	16,103
20	64,84	22,288

5.2 Static Structural

After transferring the generated rudder model to ANSYS and choosing the material of the structure, fixed support areas are designated. In this case there are five different fixed support faces as three of them are aligned in the main beam that connects the rudder to fuselage and remaining two are connected to rudder pedals with strings to rotate the vertical stabilizer.

Finishing the fixed support section, another selection of faces is required as the pressure application surface areas need to be determined. In this case there are three different faces need to be selected as the cross wind only applies from one side to the rudder structure in this analysis.

Once the required surfaces have been selected, in order to complete the analysis and acquire realistic results certain amount of mesh needs to be obtained over the rudder model and the amount of meshes should be verified by making a mesh accuracy diagram.

5.2.1 Mesh Accuracy

To obtain an accurate result Different meshes were obtained in 13 different element sizes. With the obtained data a diagram was obtained. Reading through the obtained diagram an interval of 0, 0115 – 0,011 was chosen due its optimally similar results. All of the mesh accuracy process were made in the Knot level of 15 where no flutter occurs which is also the maximum safety limit for landing for training aircrafts of similar sizes.

Table 5. 2 Mesh accuracy table.

Element Size	Mesh-Node	Tot-Def	Eqv-Stress	Eqv-Strain
0,04	11530	9,47E-06	1,18E+06	1,91E-05
0,03	18582	1,88E-05	1,89E+06	3,20E-05
0,02	37683	4,07E-05	2,90E+06	4,91E-05
0,018	44583	4,46E-05	1,56E+06	3,34E-05
0,015	62414	5,49E-05	3,50E+06	5,93E-05
0,014	68867	5,85E-05	1,94E+06	4,04E-05
0,013	79738	6,22E-05	2,00E+06	4,03E-05
0,012	92570	6,58E-05	2,26E+06	4,37E-05
0,0115	102753	6,66E-05	2,96E+06	4,53E-05
0,011	104225	6,72E-05	2,98E+06	4,59E-05

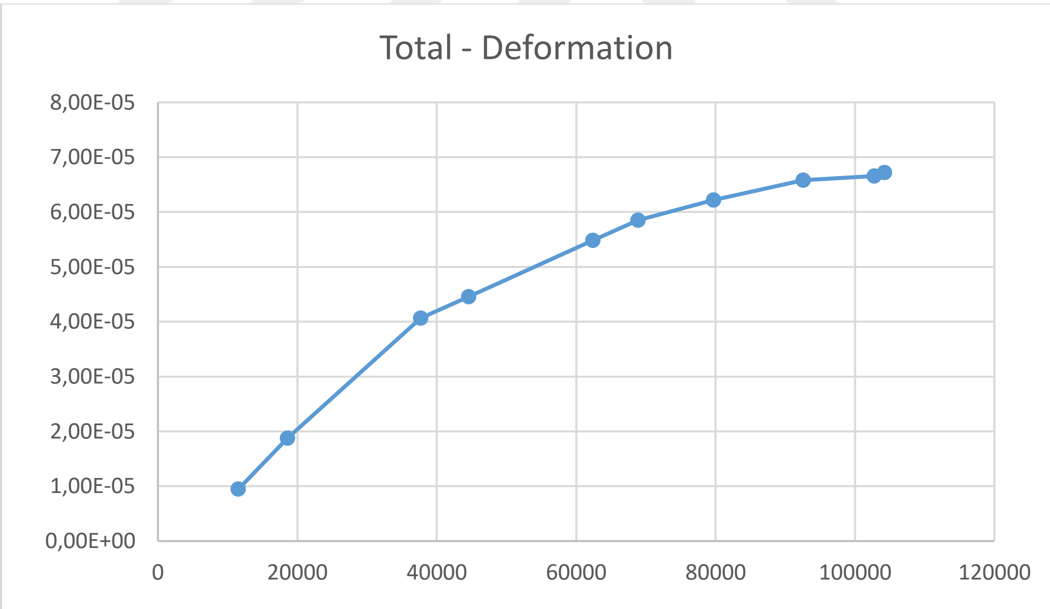

Figure 5. 1 Mesh accuracy graph.

5.2.1.1 Crosswind at 15 Knots

When the Crosswind level is at 15 Knots due to rudder geometry and the angle between wind normal direction and surface the pressure has been calculated as 12,537 N. As the result of this analysis, it is observed that the total deformation as 6,6916e-5, Equivalent Stress as 3,1167e6 and Equivalent Strain as 4,7063e-5. No frequency values were obtained due to flutter not occurring at this crosswind level.

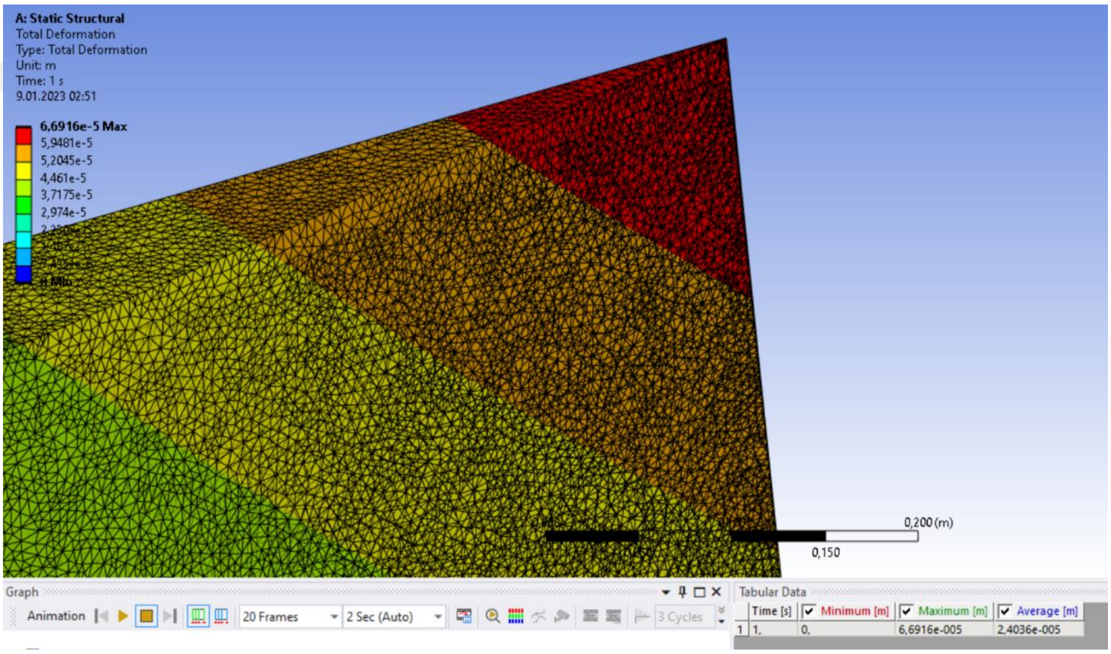

Figure 5. 2 Total deformation at 15 Knots of crosswind.

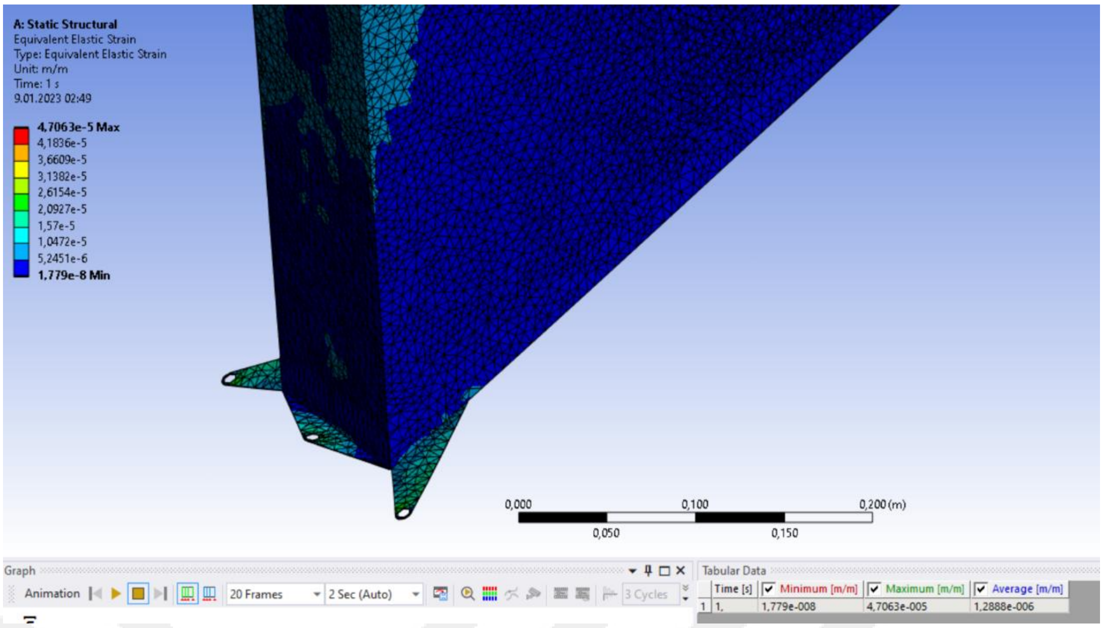

Figure 5. 3 Equivalent elastic strain at 15 Knots of crosswind.

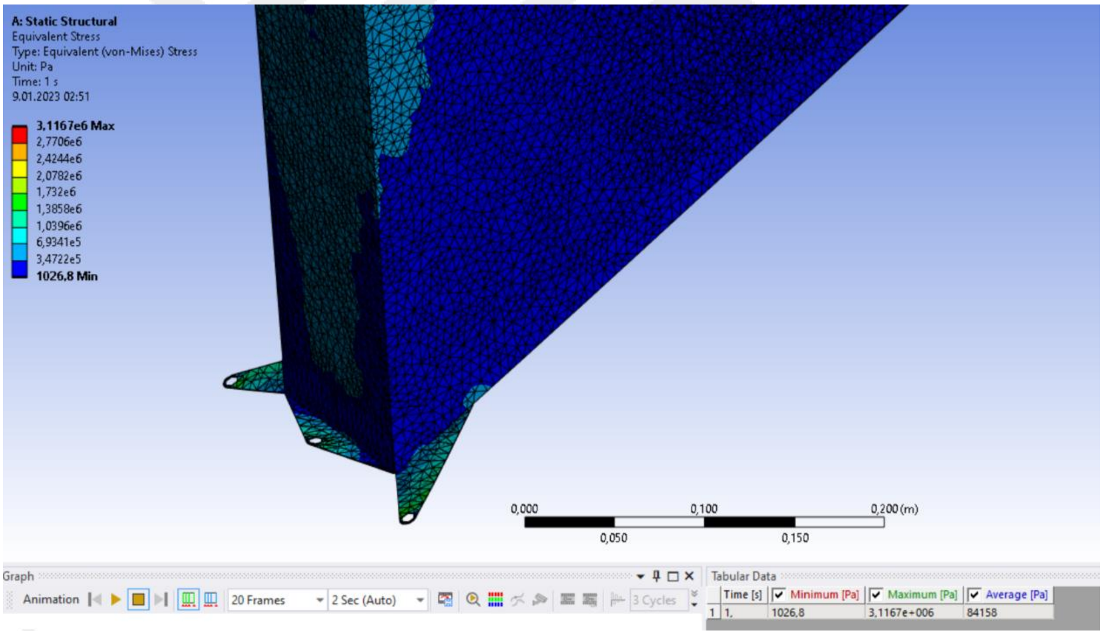

Figure 5. 4 Equivalent stress at 15 Knots of crosswind.

5.2.1.2 Crosswind at 17 Knots

When the Crosswind level is at 17 Knots due to rudder geometry and the angle between wind normal direction and surface the pressure has been calculated as 16,103 N. As the result of this analysis, it is observed that the total deformation as 8,5949e-5, Equivalent Stress as 4,0033e6 and Equivalent Strain as 6,045e-5. No frequency values were obtained due to flutter not occurring at this crosswind level.

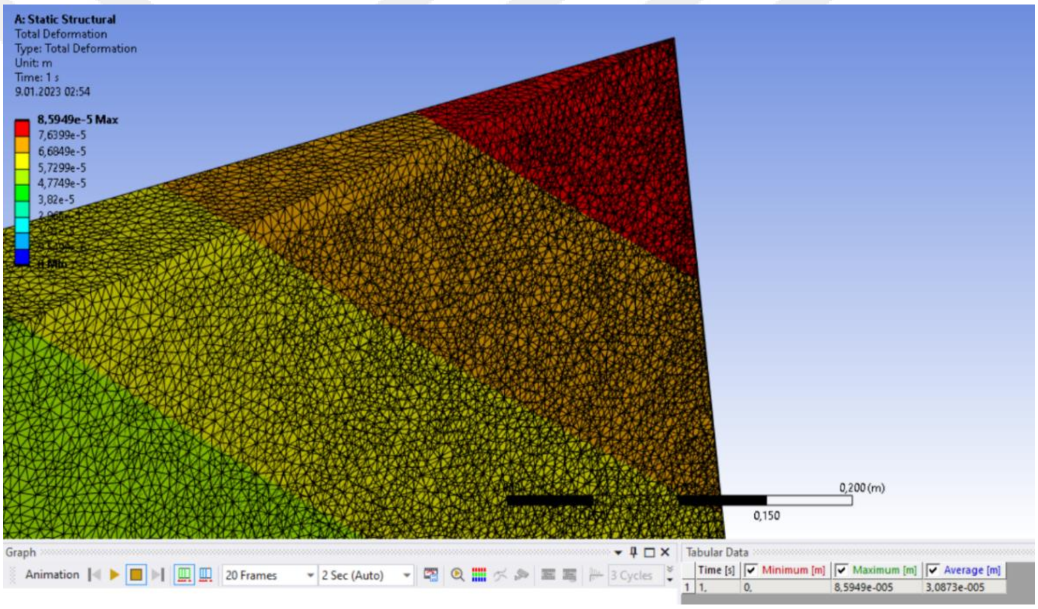

Figure 5. 5 Total deformation at 17 Knots of crosswind.

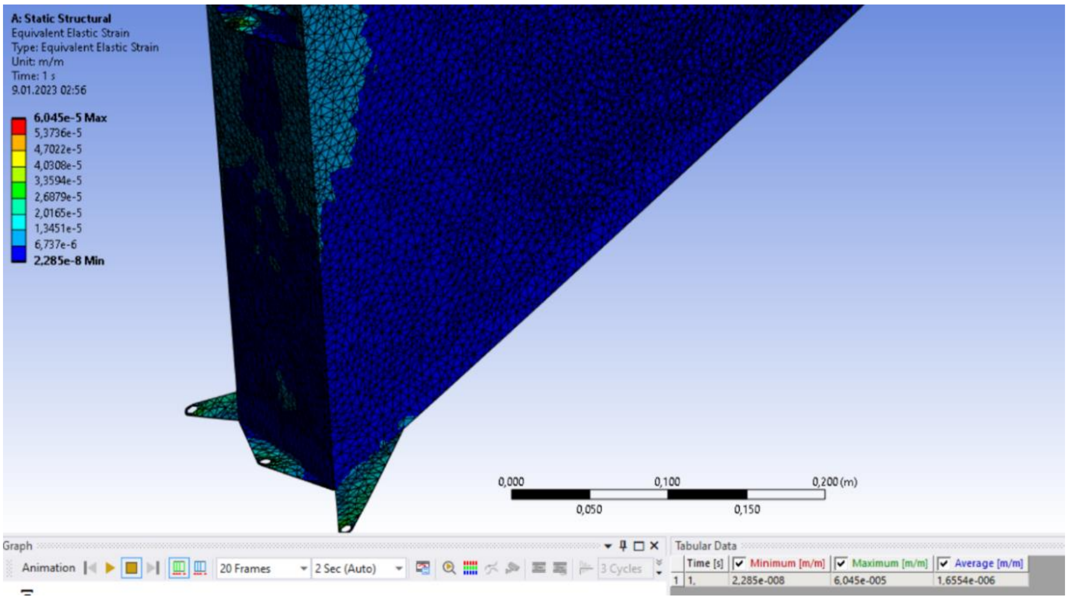

Figure 5. 6 Equivalent Elastic Strain at 17 Knots of Crosswind.

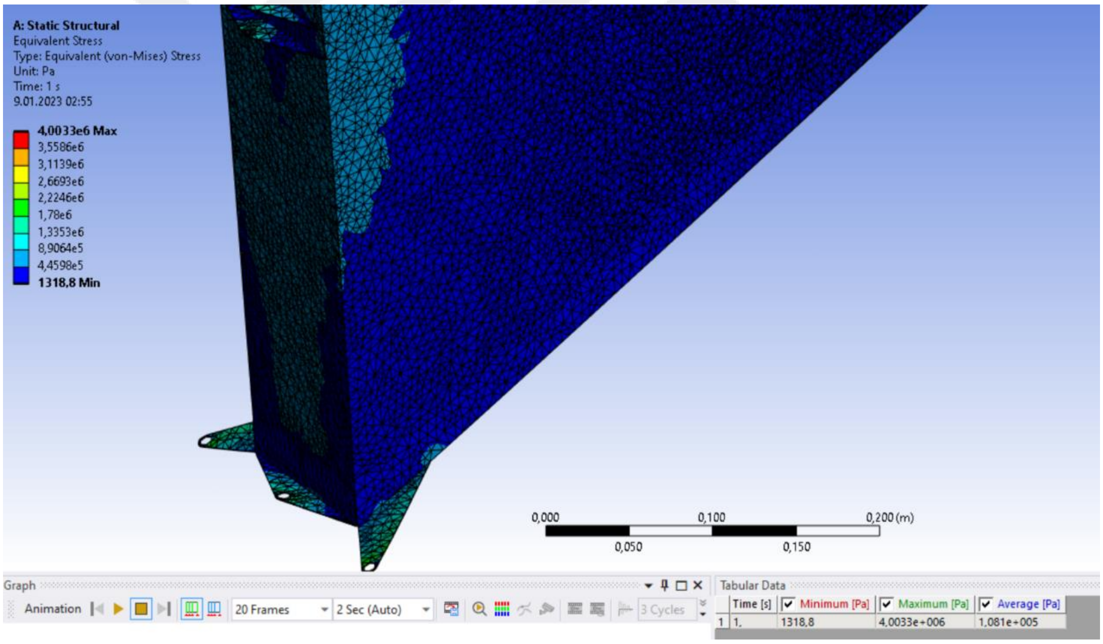

Figure 5. 7 Equivalent stress at 17 Knots of crosswind.

5.2.1.3 Crosswind at 20 Knots

When the Crosswind level is at 20 Knots due to rudder geometry and the angle between wind normal direction and surface the pressure has been calculated as 22,288 N. As the result of this analysis, it is observed that the total deformation as 11,896e-5, Equivalent Stress as 5,5409e6 and Equivalent Strain as 8,3668e-5. Crosswind occurring at 30% more than the safety guideline limit has led to the occurrence of Flutter.

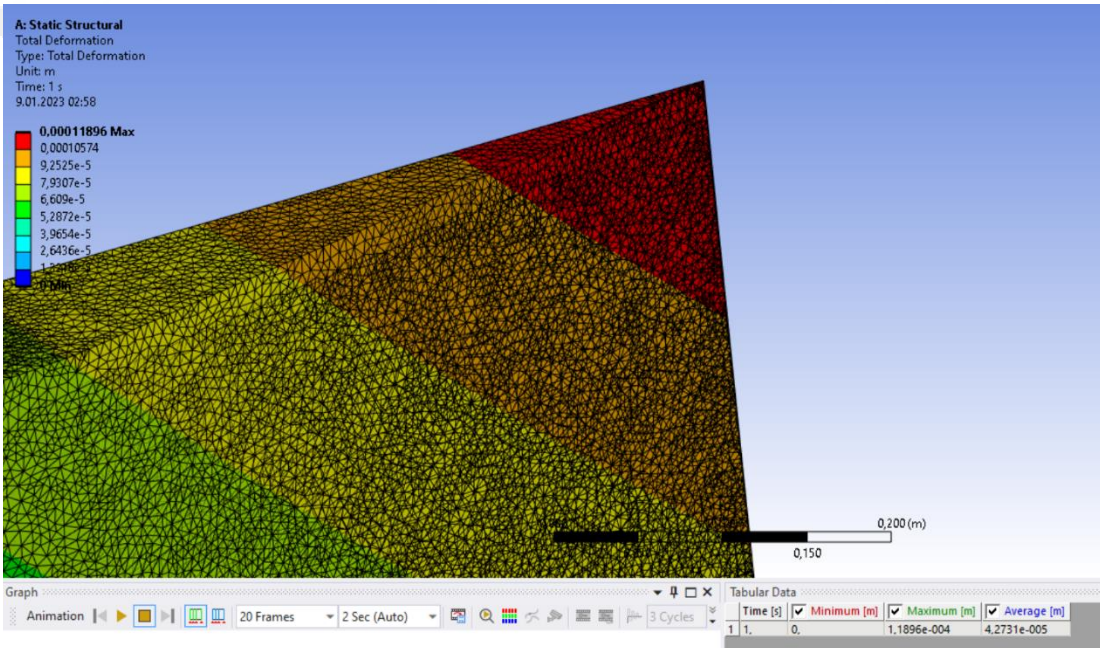

Figure 5. 8 Total deformation at 20 Knots of crosswind.

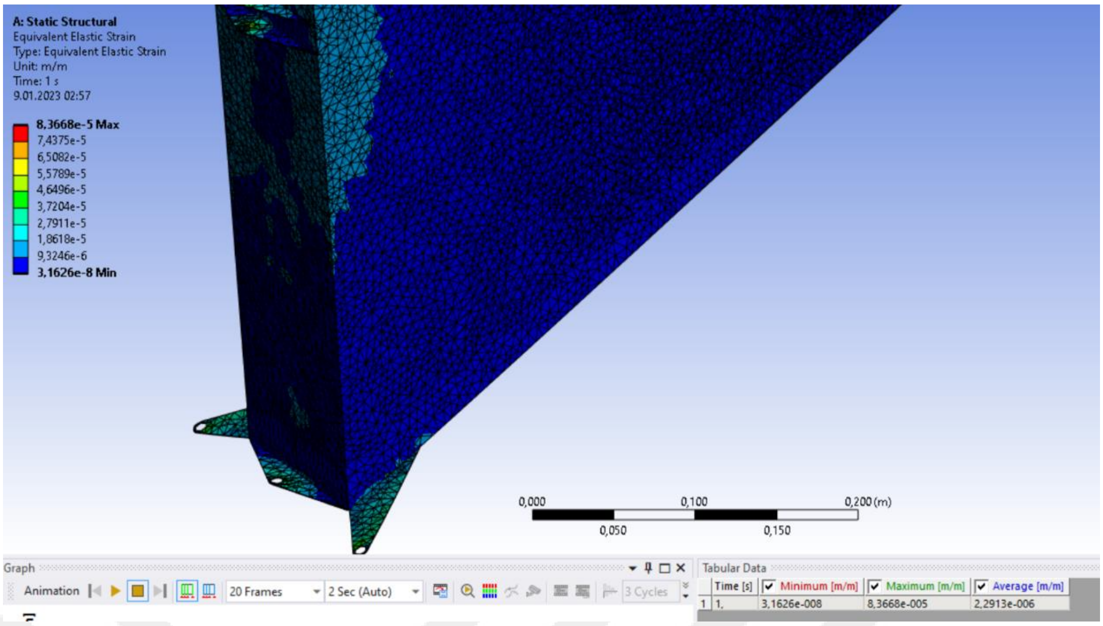

Figure 5. 9 Equivalent elastic strain at 20 Knots of crosswind.

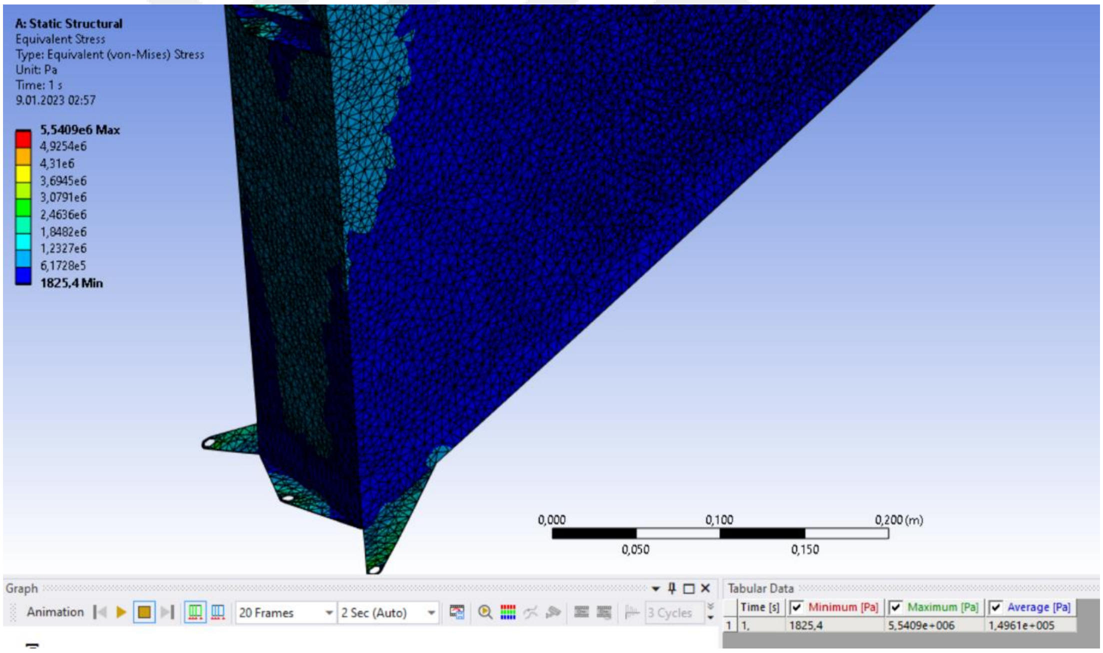

Figure 5. 10 Equivalent stress at 20 Knots of crosswind.

5.3 Modal Analysis

The CAD model of rudder that was created in SOLIDWORKS that has the element size of 0,0113 and consists of 100 268 mesh nodes were put through a modal analysis. Only at the Knot level of 20, which is 30% above the determined FAA limit for similar sizes of training aircrafts flutter was observed. With the deformation of 1.4962.

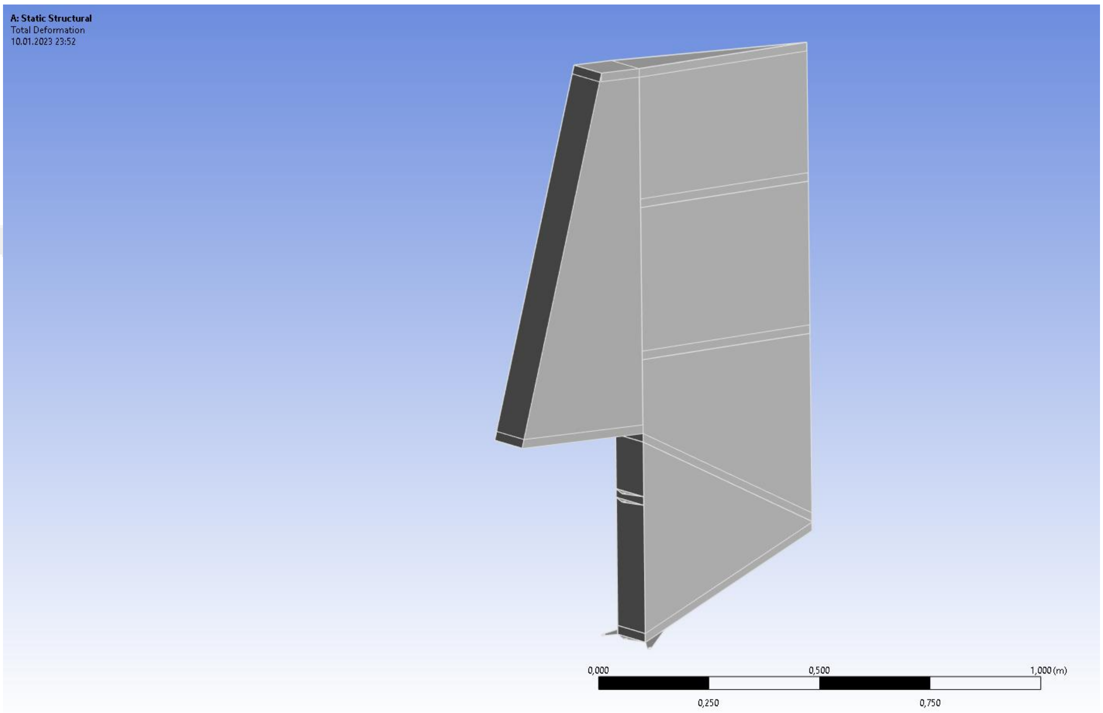

Figure 5. 11 Rudder structural model.

After meshing vertical stabilizer appropriate boundary condition was applied to structure.

Regarding the main frame of the vertical stabilizer is riveted on a rotational vertical cylinder and the bottom of this structure is riveted to a string system that connects to the rudder pedals the motion in x and z directions and rotation about y axis are prevented.

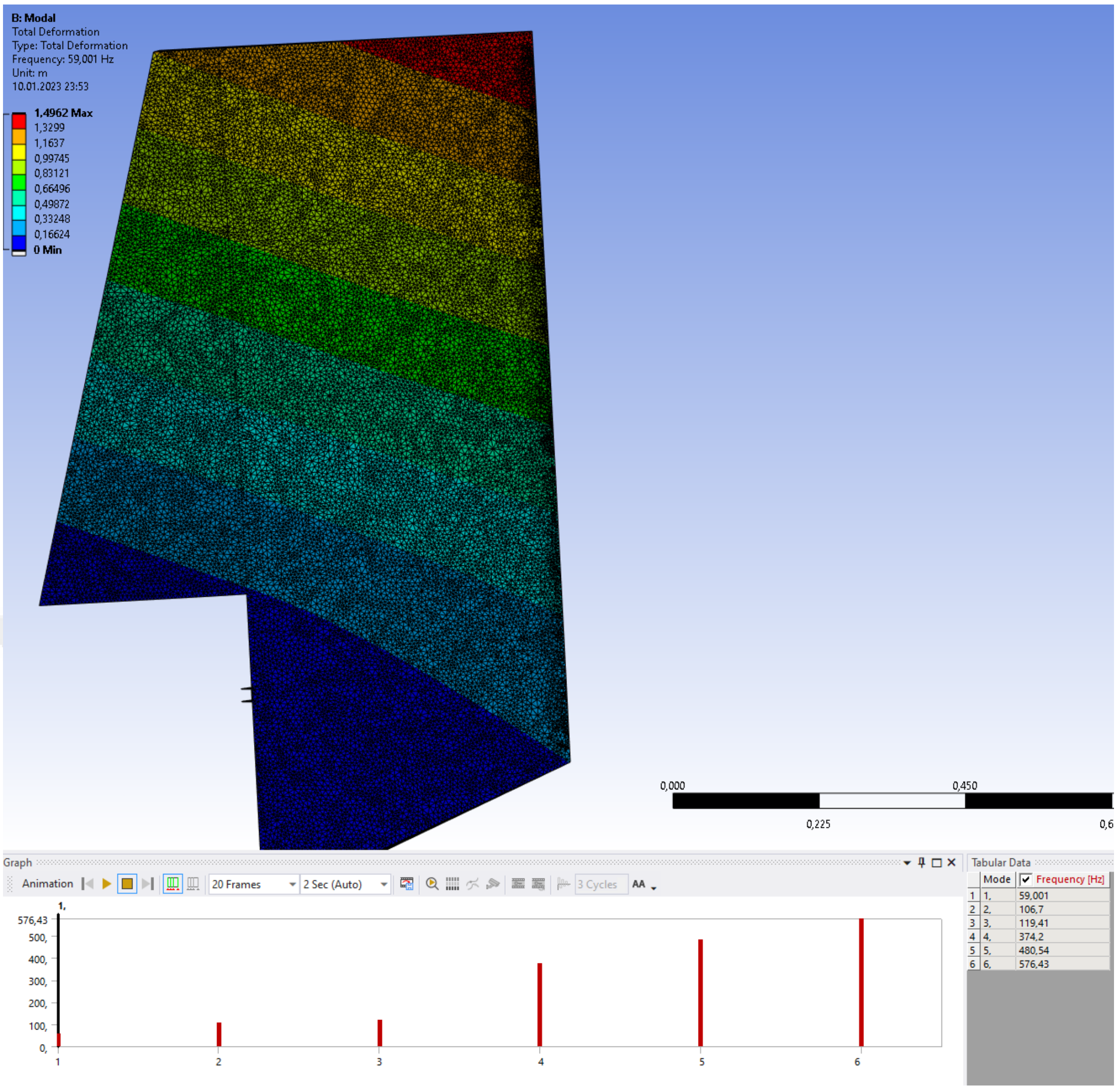

Figure 5. 12 The results of normal modes from the ANSYS analysis previously given.

5.4 Flutter Occurrence

As the result of this analysis, it is observed that the total modal deformation as 1,4962.

Table 5. 3 Frequencies at different modes.

Mode	Frequency [Hz]
1	59,001
2	106,7
3	119,41
4	374,2
5	480,54
6	576,43

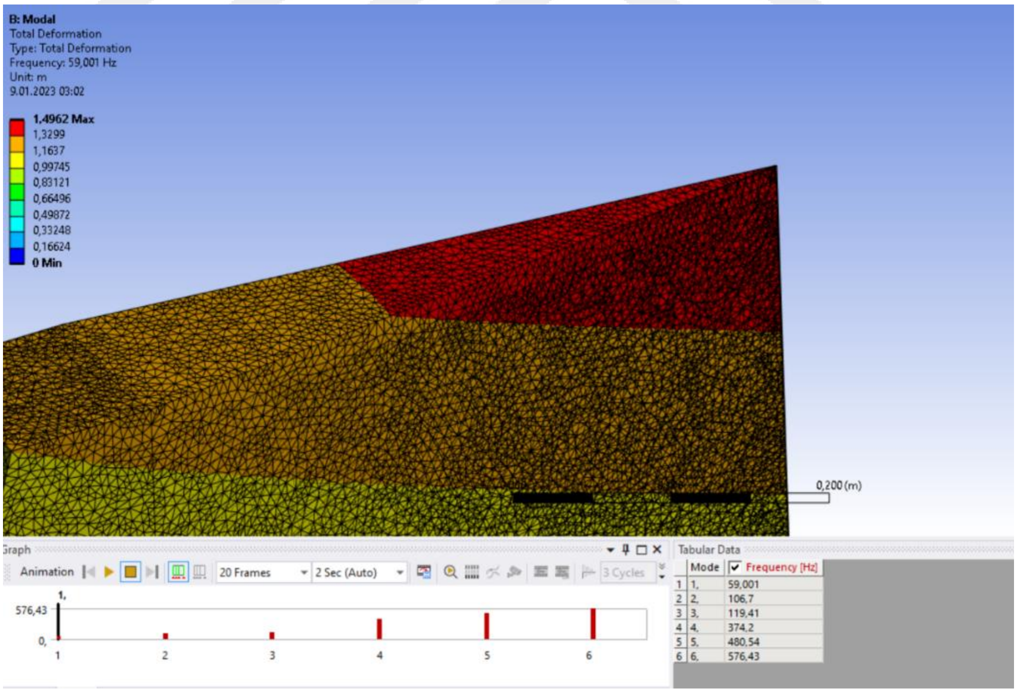

Figure 5. 13 Total deformation of modal analysis at 20 Knots of crosswind.

CHAPTER VI

CONCLUSION AND RECOMMENDATIONS

6.1 Conclusion

In the survey conducted between the years of 1950-2021; it has been observed that four articles on the relevant subject were published in the years 2000-2020 at most. It has been observed that no studies have been conducted on the effect of crosswind with flutter.

With the help of this survey the data about the crosswind speed limits upon landing has been acquired and a generic model for a training aircraft vertical stabilizer model has been created using. And this created generic model is put through and analysis using the Doublet-Lattice method along with the data acquired for crosswinds.

As a result, it is found that upon exceeding the limits set by FAA for crosswind speed on landing, flutter occurs and poses a danger of certain fatalities due to instability and possibility of destructive oscillatory movement.

6.2 Recommendations for Future Work

In the future if the focus of the flutter studies, shift towards the cross-wind effect to the flutter of the aircrafts upon landings, this study can be used as a base point to learn about flutter and different approaches to it. It is observed that as much as the surface of the structure effects the load caused by the aerodynamic forces, the resistance of the structure highly depends on the frame structure within the vertical stabilizer and the material it consists of.

And if a successful study is conducted, safer and more comfortable landings in stronger cases of cross-winds avoiding time loss and safety hazards can be obtained. Also, it is possible to have cost efficient flights as this study can reduce repair costs due to eliminating destructive effects of the vibration and exerted force by cross-wind.

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