A Review on Design Optimization of an Aircraft Wing with Emphasis on Vibration Characteristics

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Abstract *- It is essential that the structural stability of the aircraft wings is a major consideration in the design of the aircraft. Many studies are being carried out for the design of the wings across the globe by the researches to strengthen the aircraft wings for steady and sturdy structures for dynamic conditions.*

The design of the aircraft wing using NACA standards is been discussed in this review. The wing analysis is carried out by using computer numerical analysis tool, viz., CAD/CAE and CFD. The optimization of the aircraft wing is effectively achieved by considering different material properties, loading conditions and dimensions with different flying conditions. The modal analysis is considered to analyse the wing to determine the natural frequency for vibration characteristics of the wing structure. The proposed work is identified in carrying out the wing analysis for vibration characteristics using computational tools, and then a prototype of wing structure. The validation of the prototype can be done by experimental method for the optimized wing design.

Keywords — *Aircraft Wing structure, Stress analysis, Modal analysis, CATIA V5R19, CFD*

I. INTRODUCTION

The main function of the wing is to produce enough lift (L). Drag (D) and nose-down pitching moment (M) are the two components of the wing. The primary aim of the wing design is to maximize the lift and minimize the drag and nose-down pitching moment. Because of the pressure difference between lower and upper surface (based on boundary layer theory) the lift is produced, so the wing is considered as the lifting surface.

The specific wing design depends upon many aspects for example, dimensions, load, and application of the aircraft, required landing speed, and desired rate of climb. In some aircraft, the space available in the wing is used for fuel tank construction to store the fuel. Based on the pilot seated in the aircraft the wings are designated as right and left wing.

A station numbering system is used on large assemblies for aircraft to locate stations such as fuselage stations (FS) designate location along the length of the aircraft, increasing from nose to tail. Generally station 0 is somewhere in front of the airplane. One reason for this is that if the airplane grows longer, there still won't be any negative stations. Water lines (WL) designate location in the height of the aircraft, from ground up. Butt lines (BL) designate location left/right on the aircraft, generally centered in the middle. A butt line represents the stations along the wing as shown in **fig.1.1.**

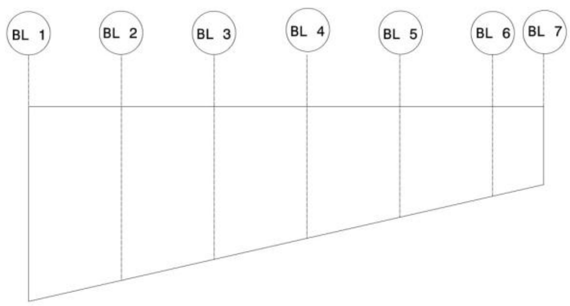


Figure.1.1: Wing station lines

The wing structures in the navy aircraft are constructed by using metals, usually the cantilever design is used; that is, no external support is required. Usually wings are of the stress-skin type. This means the skin is part of the wing structure and carries partial loads and stresses. The internal structure is made of spars, ribs and stringers spars are running along the length of the wing and ribs are placed along chord wise. Spars are considered as the main structural members of the wing, and are often mentioned as 'beams'.

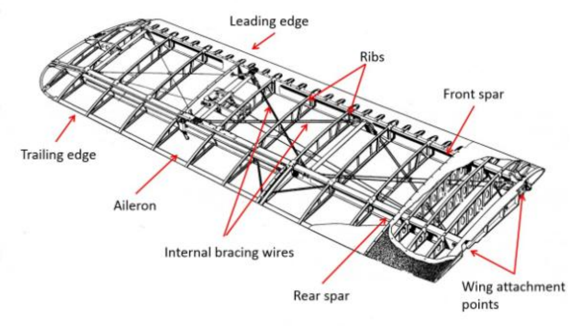


Figure.1.2: Wing construction.

One of the methods used to construct the wing is shown in **Figure. 1.2 [1],** in this picture; it consists of two primary spars along the span. Ribs are placed laterally in between the spars to give aerodynamic shape to the wing. When two spars are used in the construction of wing then it is called 'two-spar' constructed wing. Spars extend from fuselage to the wing tip and constitute primary structural member of the wing. The spars provide good bending strength. The air load is transferred from wing skin to the ribs and from ribs to the spars. Ribs placed towards the leading edge are called nose ribs, ribs placed between two spars are called intermediate ribs and ribs towards the trailing edge are called trailing edge ribs. Wing analysis is complex and time consuming process. Analysis complexity can be resolved by optimizing the wing structure. Numerical Methods like FEM is used to simplify the analysis.

II. LITERATURE REVIEW

The purpose of the literature survey is to study the works of different researchers concerned with the detailed study of the air craft wing design. Also to find out the scope for any new methods of design by which the design process is made simple, robust, less time consuming and cost effective. The literature survey is entirely based on the previous research methods. It is desired to explore the application of the fundamental properties such as vibration which plays an important role in the failure of the structure. Hence the literature survey is carried out emphasizing the structural design of the aircraft wing subjected to vibration.

Design OF Airfoil or Selection OF Airfoil:

The airfoil design is a time consuming and a complex process. The knowledge of aerodynamics is the requisite of expertise. Airfoil aerodynamic properties can be verified by wind tunnel test, which is most expensive. Huge aircraft production firms, viz., Boeing and Airbus, have sufficient budget and experts to design their own airfoil. Designing their own airfoil is not economical for small aircraft manufacturing companies, investigational aircraft producers and homebuilt manufacturers. Best method for small aircraft manufacturing firms is to select airfoils from the standard data available in several books or websites. Two standard airfoil resources are NACA and Eppler. Maximum aircraft designers select airfoil sections from NACA standards.

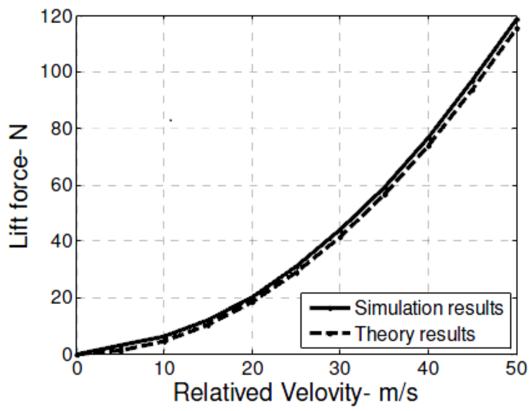
National Advisory Committee for Aeronautics, (NACA):

Since 1930's some families of airfoil sections and camber lines were arrived by the NACA was a U.S. federal agency. General and military aircraft, as well as propellers and helicopter blades were using many of these airfoil shapes at wing and tail sections. The ordinates for number of perticular airfoils of these series at rough stations of data points were published in a series of NACA reports. When carrying out parametric studies on results of variables such as thickness, location of maximum thickness, leading edge radius, location of maximum camber and others, it is difficult to obtain the ordinates of the required shapes correctly and quickly. To overcome these difficulties the NASA Langley Research Centre developed computer programs for standard airfoil generation.

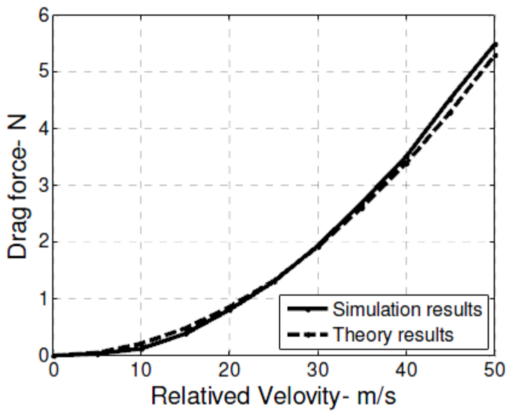
The shape of the NACA airfoils is described using a series of digits following the word "NACA". The parameters in the numerical code can be entered into equations to precisely generate the cross-section of the airfoil and calculate its properties.

The contributions of different researchers, who worked on the design of aircraft wing, using NACA standards, have been discussed in the following paragraphs.

Nguyen Minh Triet et.al in their paper they expressed their view regarding difficulty in solving analytically the aerodynamic problems. Huge experimental expenses are involved in solving aerodynamic problems. Hence they preferred numerical methods. They modelled aircraft wing using standard NACA 2412 airfoil and carried out computational fluid dynamic (CFD) simulation using ANSYS Fluent and analyzed the pressure and velocity distribution on the surface of wing. Using ANSYS Structural module they calculated drag and lift forces. Additionally, the coefficients of drag and lift forces can be calculated through the data obtained when the relative velocity inlet between the airflow and airfoil changes from 0 to 50 m/s. Simulation results were compared with theoretical results as shown in Fig. 2.1 [3]



a. Relative velocity versus Lift.



b. Relative velocity versus Drag.

Figure.2.1: Comparison of theoretical and simulation results

Kakumani Sureka and R Satya Meher in their paper they modelled A300 aircraft wing using standard NACA 64215 airfoil with spars and ribs was done using the CAD software, CATIA V5 R20, and later using ANSYS WORKBENCH (the finite element analysis (FEA) software) structural analysis on wing skeleton was carried out. It was observed that difference between the values of equivalent stress, deformation; max principle stress, stress intensity and shear stress of Aluminium alloy and Aluminium alloy7068 are minimal. The results obtained were validated and the differences between the two result values were negligible. They arrived to the conclusion that Aluminium alloy 7068 is preferred over Aluminium alloy in order to give the more strength to the structure. [4]

Sudhir Reddy Konayapalli and Y Sujatha discussed the aircraft wing design. It was modelled using standard NACA 4412 airfoil in CAD software, CATIA V5 R20. They imported CATIA V5 model to ANSYS 14.5 software. They observed from the fluent analysis that the dynamic pressure on leading edge was decreasing with increasing the angle of attack. Static pressure on lower surface was increasing with increase in angle of attack. They concluded that static pressure was increased with increase in the angle of attack. Dynamic pressure on the lower surface was decreasing with increasing angle of attack whereas static pressure was increasing on lower surface. They concluded that dynamic pressure was increased with increasing the angle of attack. [5]

Guguloth Kavya et.al in their study, an aircraft wing was designed and modelled in CAD software, Pro/Engineer. They have not mentioned the type of NACA profile used. They modified the wing by adding ribs and spars. Static analysis was done on the wing by applying air pressure for three materials like S-Glass, Kevlar 49 and Boron fibre because of their high strength to weight ratio. Using ANSYS Workbench Structural analysis on wing skeleton was carried out. After analysing the results, they concluded that deformation and stresses were less for wing with ribs and spars than compared with that of original wing. Modal analysis was done on the aircraft wing to determine the frequencies. They observed that frequencies were more for wing with spars and ribs but deformations are less. After conducting random vibration analysis, they arrived to the conclusion that the shear stress was less for modified model than original model. They concluded that the wing strength could be increased by adding ribs and spars. [6]

Lica Flore and Albert Arnau Cubillo presented the results of the dynamical behaviour on an aircraft wing structure. In their study wing structure vibration parameters have been determined dynamically using strain gauges. Researchers used strain gauges for performing vibration testing instead of using accelerometers. Change in the dynamic behaviour of the structure was determined after applying the load. They arrived at the conclusion that accelerometer gave the natural frequency values near to the excitation point but not in the exact point of excitation. They used strain gauges to measure the natural frequencies at the point of excitation and they noticed difference in results. These are given in the Table 2.1. [7]

Table 2.1: Comparison between strain gage and accelerometer natural frequencies [Hz].

Mode	1st	2nd	3rd	4th
		No Loading		
Accelerometer	9.61	47.11	50.27	98.72
Strain gauge	10.11	47.77	50.75	--
Difference	5.2%	1.4%	1.0%	
		1.5 kN Loading		
Accelerometer	11.25	49.49	50.81	--
Strain gauge	11.14	49.53	50.85	--
Difference	-1.0%	0.1%	0.1%	

In the work of Guguloth Kavya and B.C Raghukumar Reddy the aircraft wing was modelled using standard NACA 65210 airfoil in CAD software, CATIA. Dynamic analysis on wing skeleton was carried out by using ANSYS Workbench, The objective of this paper was to analyze the dynamic structural response of an aircraft wing and to simulate it for various boundary conditions, but they used same boundary conditions instead of various boundary conditions. They analyzed for two different wing models and material properties and the comparison between the results has been studied. The loading conditions are the self-weight of the wing. They extracted the output in terms natural frequencies and displacements for different mode shapes of the wing. It was concluded that the taper wing was stiffer than rectangular wing. The comparison is given in Table 2.2 [8].

Table 2.2 : Taper and Rectangular wings comparison

	Taper Wing(Aluminium)	Taper Wing(Titanium)	Rectangular Wing(Aluminium)	Rectangular Wing(Titanium)
Natural Frequency(Hz)	13.412	13.232	9.5488	9.4249
Max. Displacement(mm)	9.4031	7.4975	4.3567	3.4751

T.S.Vinoth Kumar et.al in their work the aircraft wing was modelled using standard NACA 64A215 airfoil at the root, NACA 64A210 at the tip in CAD software, CATIA V5 R20.In this paper they have concentrated on analysing and preliminary sizing of an aircraft wing used for training the pilots. The important objective was to fix suitable structure within the specified envelope and to calculate the obvious lift-off weight, stress distribution, wing loading, take-off distance, lesser frequency modes of vibration and velocity of stall. Optimization was carried out by using traditional engineering theories and MSC NASTRAN/PATRAN package. They assumed web and skin as shell elements, stringer, flange, and spar as beam elements, with these assumptions they optimized the design which satisfies the stability and strength criteria. Then they calculated the factor of safety of wing structure. [9]

Farrukh Mazhar and Abdul Munem Khan were used implicit CAD model along with aerodynamic computational fluid dynamic analysis of the wing as design input. The stiffness and strength analysis of the Unmanned Aerial Vehicle (UAV) wing was carried out using FEA ANSYS software. They successfully explored the application of the computational techniques in design. They used special approach called Artificial Neural Networks to apply Aerodynamic loads on the wing structure as pressure functions. Effects of material, lay-up and geometry variation were also analyzed to choose the best feasible combination with stiffness, optimum strength, minimum cost and weight. The concluded wing has made up of two spars and was built using composite material. They concluded that the wing made up of composite material was light in weight as compared to same wing made using aluminium, and strong enough in meeting all in-flight loads and FOS. [10]

Beulah Saripalli et.al in this paper, the wing model developed in CATIAV5 was retrieved to ANSYS to carryout structural analysis by applying air pressure for two materials Aluminium - Carbon fibre and Aluminium - Aramid fibre. They observed that the deformation and stress were less for Carbon fibre than Aramid fibre. Dynamic analyses were also carried out on the aircraft wing for the similar two materials to determine the natural frequencies in Hz and were shown in the Table 2.3.

Table. 2.3: Comparison of overall (total) deformation of three different materials using modal analysis

Mode No	Total deformation in mm		
	Aramid fibre	Carbon fibre	Plain Wing
1	8.428	7.8563	6.3353
2	9.4287	9.453	7.0876
3	15.828	17.384	11.898
4	12.96	14.372	10.96
5	15.237	14.739	11.454

From the results, they concluded that natural frequencies were more for Aramid fibre than carbon fibre, so the vibrations were more when Aramid fibre was used. CFD analysis was done on the wing to determine the lift and drag forces by changing angle of attacks. The angle of attack taken was 20 and 40. They observed that, the drag force was less for 20 angle of attack. They observed that by decreasing the angle of attack, the drag force was reduced. The stress produced when Aramid fibre was used was slightly more than that of Carbon fibre, but by vibration analysis, Aramid fibre was better. They observed that the hybrid composite – Aluminium wing produce fine results when analysed under pressure and frequencies when compared to a basic Aluminium wing which is used today [11]

III. CONCLUSIONS

The Computer Aided Design Tools and NACA standards have been accomplished by many researchers to optimize the wing structure. The vibration characteristics of the wing structures are studied by modal analysis to find the natural frequency for different materials considered for the wing structures. But there exist a scope for a detailed analysis of the wing structure in dynamic conditions. The use of computer aided engineering procedures to model, analyze and optimize proves to be the most economic, reliable, and faster and user friendly method to be adopted by the researchers and the engineers to cope up the industry requirements for design changes.

The proposed research can find a place in carrying out vibration characteristics for air craft wing design. The need for the simulation of the wing is another requirement in the design phase itself. Hence the objectives of the proposed research work would be focused on modeling the aircraft wing considering the NACA standards for aerofoil section, with spars and ribs, using CAD software and then carrying out CFD simulation. The Noise, Vibration and Harshness (NVH) studies can leads to comprehensive design of the aircraft wing for sturdy and stable structure. The aircraft wing design can be modified or optimized by using this method would lead to a new method to incorporate the NVH problems in aircraft design using CAE approach.

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