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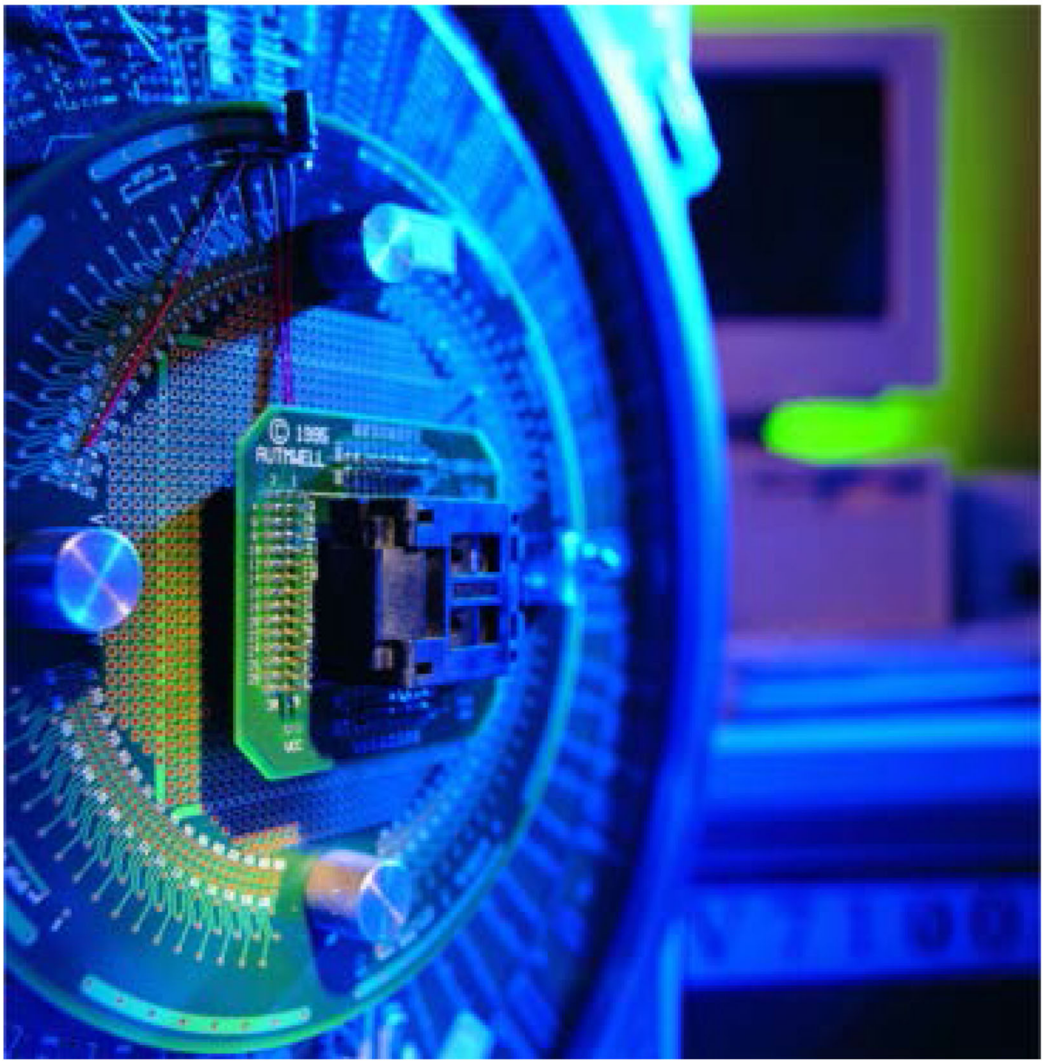

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Aerodynamic Performance Enhancement of Supersonic 2D Missile Using ANSYS

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Abstract Missile is a self-propelled vehicle flying at supersonic speeds. Their payloads are usually explosive and are also known as warheads. These warheads are used to destroy a pre-set target. The aim of this paper is to optimize the values of the lift and drag forces on the given missile for better aerodynamic performance, by carrying out numerical simulations over the supersonic missile by varying the angle of attack through a set of suitable boundary conditions, while keeping the Mach number of the missile as a fixed parameter. Aerodynamic performance of the missile is studied by varying the angle of attack from 0 to 12 degrees. For every angle of attack, the coefficient of lift and coefficient of drag variations were studied in detail and were compared with the existing literature survey so as to obtain the maximum value of C_L/C_D ratio in order to improve the efficiency. A model of the missile was designed to-scale on Space Claim and the flow analysis was done on FLUENT standalone system using ANSYS 16 workbench. The results obtained, were in the form of flow contours of parameters such as velocity, temperature, density, pressure and turbulence. Through these flow contours the maximum and minimum values of all parameters, as well as the variation in these parameters were estimated. From the numerical analysis it was found that maximum value of C_L/C_D ratio was 2.5 at 12^o angle of attack. It was also found that the velocity increased with increase in angle of attack and increased the efficiency. These results are advantageous upcoming to designers who aim to build aerodynamically efficient missiles.

Keywords Aerodynamic, Efficiency, Missile, Numerical Analysis, Performance, Angle of Attack

1. Introduction

Missile is a self-propelled weapon often having a type of guidance system and usually carries a payload consisting of explosives known as warheads, capable of causing mass destruction. Missiles are designed in order to support the environmental conditions they are supposed to operate in. There are different types of missiles and these are classified on different basis. Basically the missiles can be either ballistic or cruise. The cruise missiles are further classified on the basis of speed as subsonic, supersonic and hypersonic missiles. The aerodynamic characteristics and design of all these three types of missiles will vary greatly because of the variation in the cruise speed and flight conditions. The subsonic missiles fly at Mach 0.9 and below whereas the hypersonic missile operates above Mach 5. The body and configuration of different components of the missile are designed and optimized to withstand these supersonic and hypersonic aerothermodynamic conditions. The major mechanisms used in a missile include the Guidance systems, Propulsion systems, Aerodynamic systems and Structural systems which are controlled by the fins, air frame, warhead, etc.

The aerodynamic features, also called the control surfaces of the missile, control the missile flight. The fin and tail are the major steering control surface for the missile. The purpose of a fin is to maintain the stability and orientation of the missile and to avoid deviation from flight path due to perturbation caused during flight. Types of fins include the Planar fins, Grid fins etc. The grid fins, also known as the Lattice fins have been widely used on conventional missiles as its structure is designed to avoid the blockage of the airflow at high supersonic speeds. This makes the functioning of the actuators and the control surfaces easier. Thus such missiles offer lower drag with enhanced performance. Fins offer high maneuverability at high Mach numbers and high angles of attack. Hence fin optimization is a crucial requirement for the efficient performance of a missile. This paper gives more emphasis on the performance study of supersonic cruise missile.

2. Literature Review

Song Tian et al [2], studied the rolling effect of the missile, wherein an angle of attack feedback was provided to the rolling missile through a three loop autopilot system in order to track and observe the dynamic stability of the missile. Hence, it was observed that the angle of attack played a major role in maintaining the stability of the missile. The study mostly involved the mathematical modelling and analytical solving of the problem statement. The results obtained were further verified through numerical methods. Through mathematical derivation it was found that the angle of attack feedback system optimized the missile stability.

Experimental results are the ones obtained by using a scaled down version of the actual model, also known as a prototype. This prototype is placed in a hypersonic wind tunnel or any other similar setup which artificially recreates the operational environment and is also varies certain desired parameters to manually analyze the flow patterns over the body. Experimentation, however, is a cumbersome procedure as it requires the manual recreation of parameters such as supersonic velocity, high altitude density, pressure, etc.

A majority of the flow analysis done on the missile were done through numerical techniques using Computational Fluid Dynamics (CFD) [7][8]. The software generates the calculations based mostly on the Reynolds Averaged Navier-Stokes (RANS) Equations. This is governed by the basic important equations of continuity, momentum, energy and turbulence, taking the viscous effects and boundary layer conditions into account. The results of the calculations generated through these equations lead to the different flow parameter contours over the body. Across all experiments conducted using numerical methods, it was observed that the main motive for using such techniques is to obtain accurate results of new or optimized designs without the need to setup a test rig. Before any analysis could be run, an accurate model had to be designed so as to recreate real conditions and obtain precise results. The standard procedures for all CFD computations began with the creation of an appropriate mesh. This could be either structured or unstructured type of mesh. Following the creation of mesh, the boundary conditions are set based on the working environment of desired object or body [4][5]. Initial calculations are based on the previous experiments already performed so as to provide a reference for further calculations. Hence it is possible to arrive at valid conclusions through the solution graphs and contours obtained.

3. Methodology

The missile taken to carry out this study was a standard AGARD-B model of slender, four-fin, blunt-nose configuration whose geometry was taken from [1]. The blunt nose was chosen for the missile so as to make the configuration of the missile aerodynamically efficient by minimizing the shock waves generated at the nose-tip by transferring the kinetic energy generated, to the atmosphere, thus reducing the frictional effects and on the missile body. For different turbulence models and various angles of attack on airfoil studied in detail by Armaan A. and Srinivas G. et al[9,10].

3.1. Modeling

The missile [1] was modelled in Spaceclaim using basic sketching tools with a length (L) of 763.7mm. The creation of the domain was done to analyze the nature of the flow specifically around the missile model and within the domain so as to obtain more accurate results. The domain created for the model was a rectangular extending to 1.5L upstream, 3L downstream and 2L in the cross-stream direction from the missile. After sketching the missile in SpaceClaim as shown in Fig. 1, it was modelled in Design Modeler as in Fig. 2 for surface generation of the 2-D missile and domain. Further, a subtractive Boolean was generated in order to separate the missile surface from the domain surface so as to ensure the flow moves around the missile and not through it.

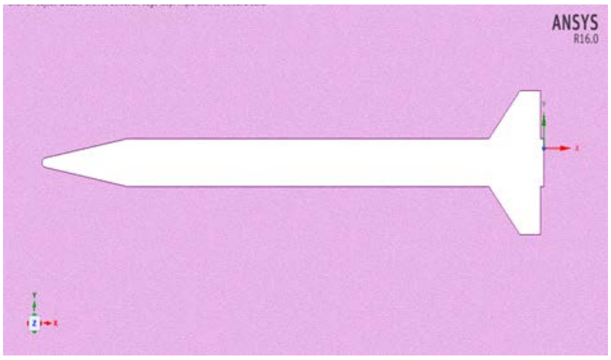


Figure 1. Model of Missile in ANSYS SpaceClaim

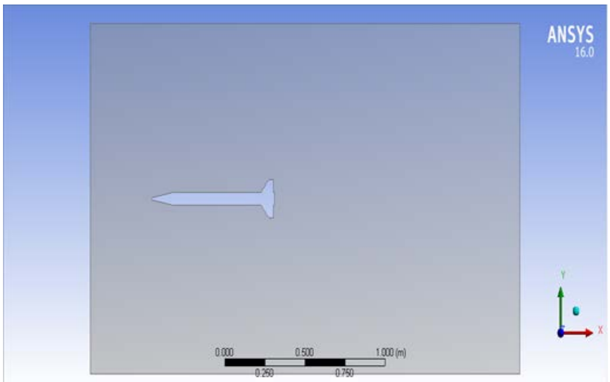


Figure 2. Model of Missile in ANSYS DesignModeler

3.2. Meshing

Finite volume approach was used for computing the flow analysis over the missile. It was required to create small element within the domain so as to obtain the required average parametric value of the individual elements in the flow field.

An unstructured grid of the rectangular domain was generated with triangular elements, with number of nodes and elements being 388756 and 766806 respectively. Body sizing was given in the form of sphere of influence around the missile body in order to refine the elements near the body within the radius of given sphere. For the missile, edge sizing was given for the individual edges of the 2D missile model by dividing the edges into appropriate number of divisions so that finer elements were created around the body. Since precise flow results were required nearer to the body surface, refinement was given with a factor of 3. The domain was considered to be a pressure far field and the edges of the missile body were considered to be the walls.

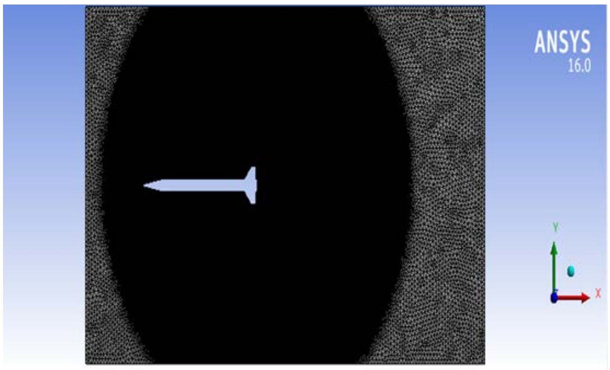


Figure 3. ANSYS Mesh showing sphere of influence.

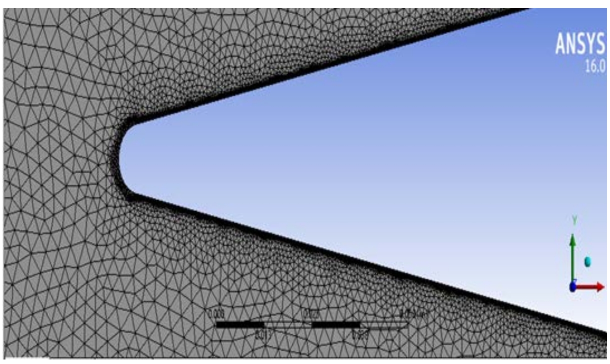


Figure 4. ANSYS Mesh showing refinement around the missile body.

3.3. Flow Setup

Since the flow is supersonic, density based solver was used in FLUENT to carry out the flow analysis. The turbulence model used was k-omega SST for better turbulence results and with the energy mode on. The fluid was assumed to be an ideal gas so as to implement the equation of state.

Boundary conditions were set for the pressure far field with respect to the pressure, which was set to be the ambient pressure at an altitude of 10200m as mentioned in the reference paper [1]. Mach number was set as a constant parameter throughout the analysis at all the angles of attack with a value of 2.5. This was one of the values taken from the reference paper [1]. The x, y components were set as the horizontal and vertical components, of the given angle of attack, respectively. This angle of attack is taken as a variable parameter ranging from 0^o to 12^o, with initial reference analysis being carried out at an angle of attack at 6.05^o, which is one of the values from the reference paper [1]. Keeping the specific dissipation rate and turbulent kinetic energy as second order equations the flux type was set as AUSM in order to take the supersonic condition into account. The setup was initialized with reference frame as relative to cell zone. The parameters to be calculated as output results were chosen as lift and drag coefficients. The convergence level was set to be as 10^{-6} and the iterations were carried out till the convergence accuracy was reached up to a maximum of 10^{-6}.

3. Grid Independence Test

The grid independence test was carried out for the initial model with an angle of attack of 6.05^o. Three different meshes were created for the given model. The number of elements in each of the meshes were 1520481, 766806 and 157326 respectively. This was achieved by varying the maximum and minimum element size of every mesh. Analysis were run using each of these three meshes individually and the best accurate result obtained was from the mesh with number of elements of 766806 and this mesh was further used to carry out the rest of the analysis with the remaining angles of attack.

As inferred from Figure 5, the closest value of C_L/C_D value of the grid independence test to that of the reference value is the value obtained from grid independence 2, and hence having the maximum value of aerodynamic efficiency among the ones obtained from the three grid independence tests.

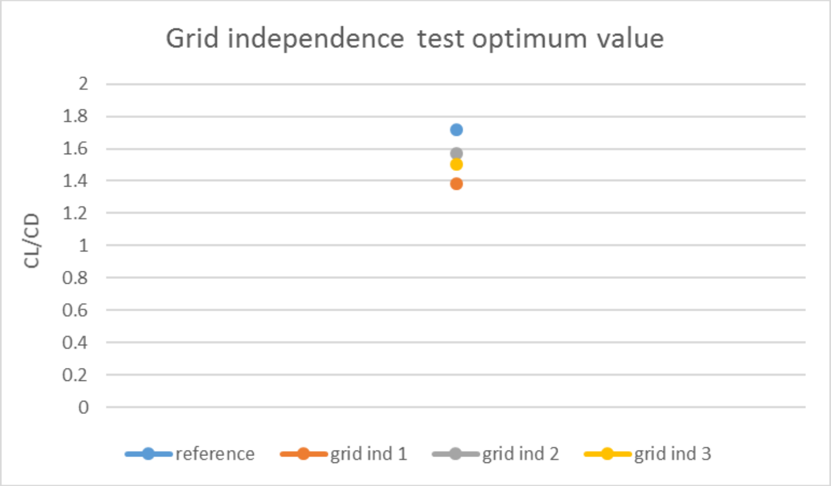


Figure 5. Comparison of grid independence test values

4. Results and Discussion

4.1. Flow Contours

From the numerical results the flow contours extracted were those of velocity, Mach number, pressure, density, temperature and turbulence.

Fig. 6 to 9 below show the flow contours of velocity, pressure, density and temperature respectively at angle of attack of 6.05°

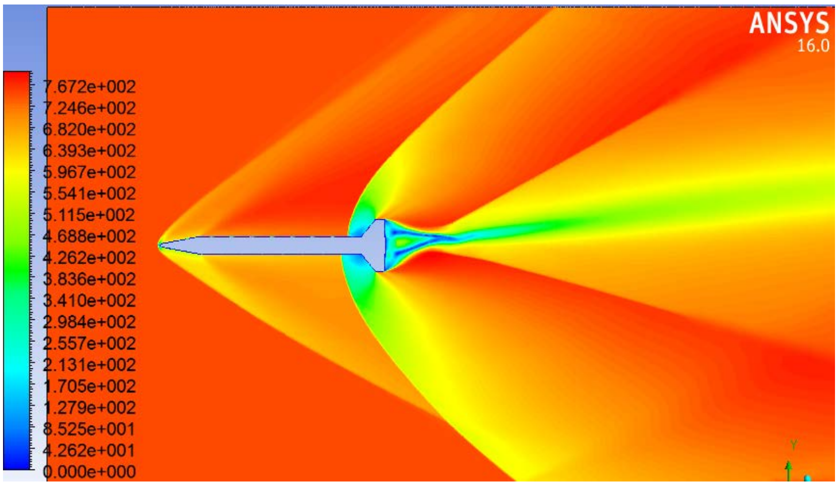
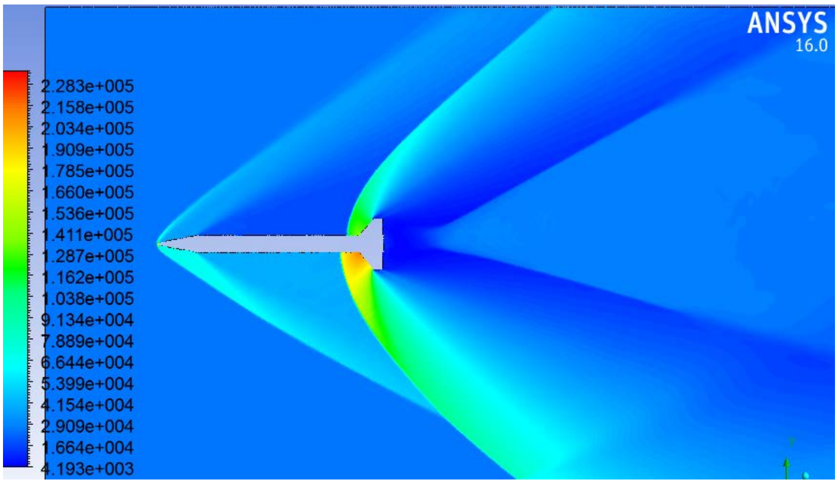
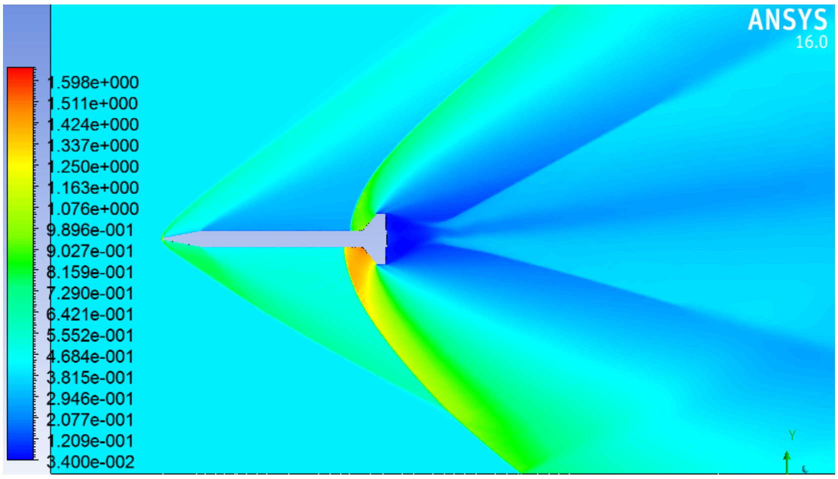
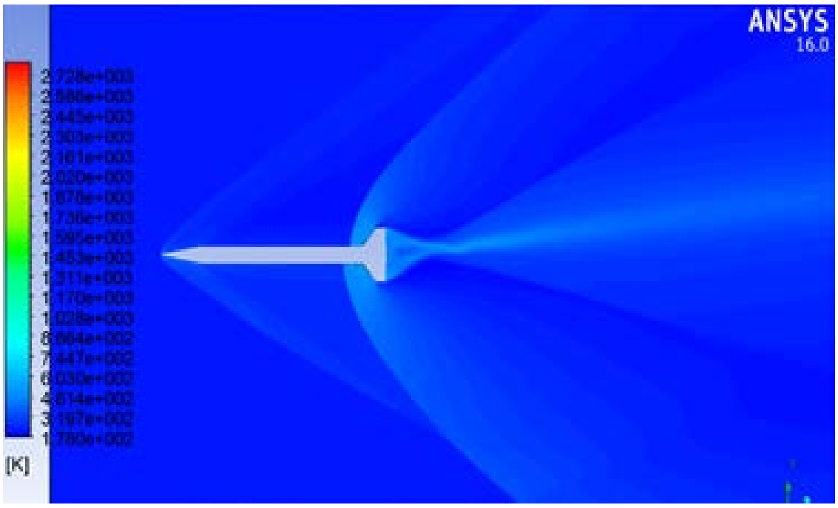
Figure	Angle of Attack (α)	Parameter	Contours
Fig. 6	6.05°	Velocity	

Fig. 7	6.05^o	Pressure	
Fig. 8	6.05^o	Density	
Fig. 9	6.05^o	Temperature	

The flow contours along with the C_L and C_D values were closely studied in order to initially validate the results of angle of attack of 6.05^o and later to check the effect of angle of attack variation on the values of C_L and C_D so as to obtain an optimum value of angle of attack for maximum value of C_L/C_D, which is the aerodynamic efficiency of the missile.

From Fig 6, which is the velocity flow contour at an angle of attack of 6.05^o, it was seen that there is one attached shock generated at the missile nose, as well as a normal shock, generated at the tail area of the missile. These shock waves slow down the flow, having very low value velocity behind the normal shock wave. Also, from Fig. 6 to 9, it was observed that the velocity values reduced, whereas the pressure, temperature and density values were found to have increased behind the shocks formed. Ahead of the fins, the flow was seen to be separated from the surface of the missile. This flow separation further saw reduction in the flow properties, having their least values after the flow separation.

Similar Flow patterns was observed when the angle of attack was varied from 0^o to 12^o, with the generation of the shock waves and flow separation at the end of the body, with the reduction in the flow parameter value of velocity whereas increase in pressure, temperature and density values as shown in Fig. 10 to 17. At a given point, the flow parameters, however, were noticed to have a greater value in higher angle of attack than in the lower angle.

Figures 10 to 16 show the flow contours of velocity, pressure, density and temperature at angles of attack of 0^o and 12^o respectively:

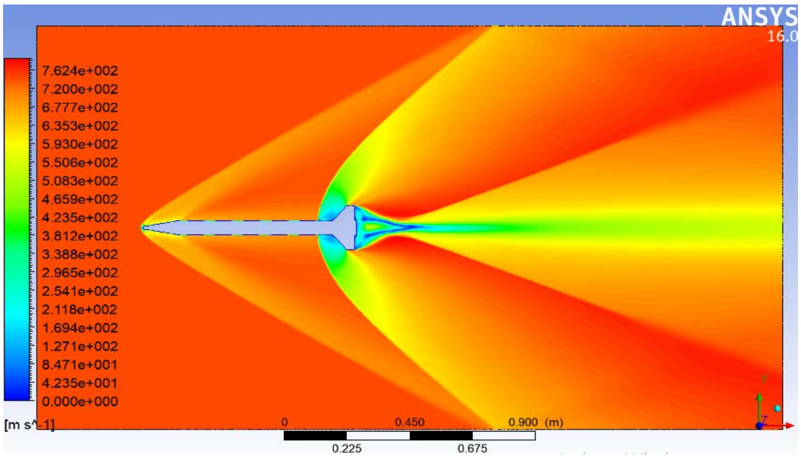
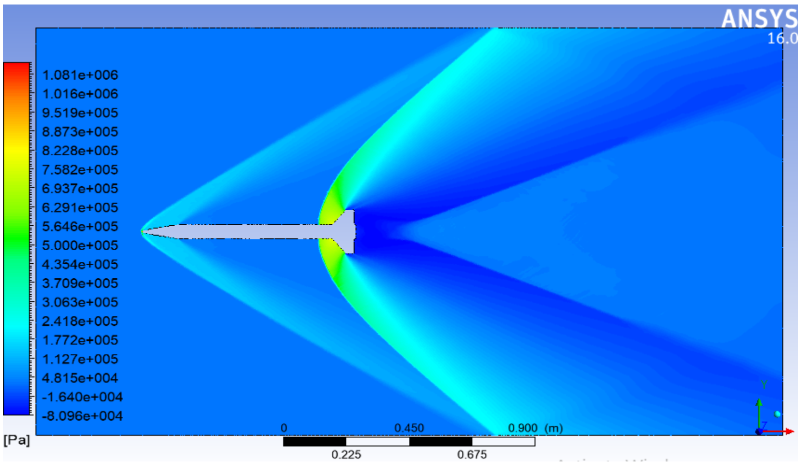
Figure	**Angle of Attack (α)**	**Parameters**	**Contours**
Fig. 10	0^o	Velocity	
Fig. 11	0^o	Pressure	

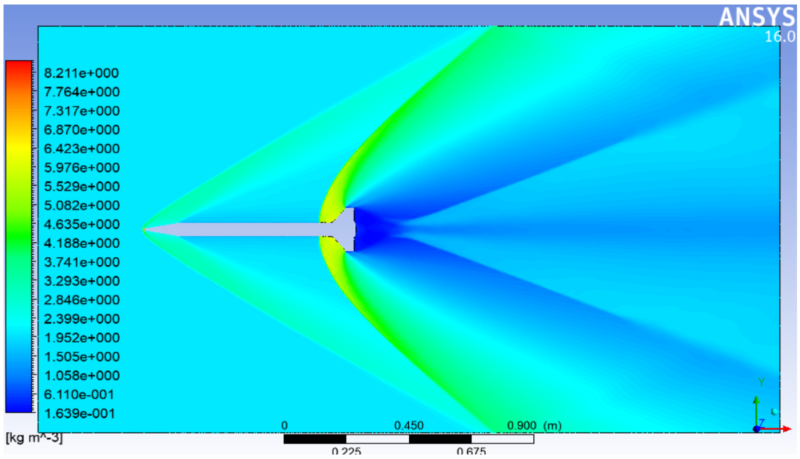
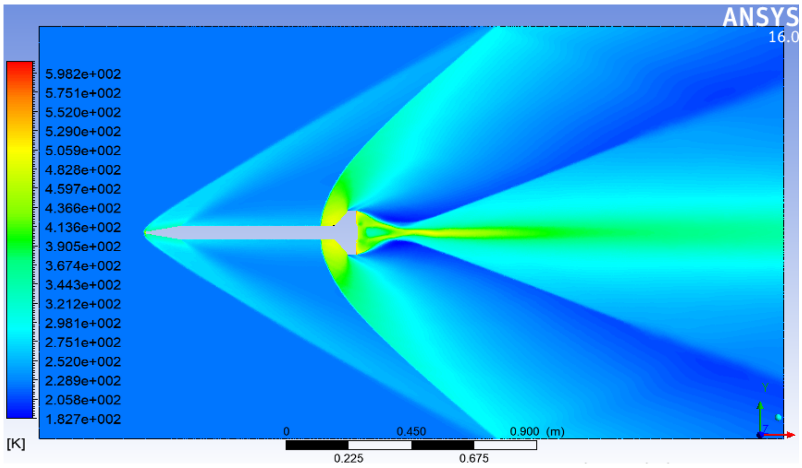
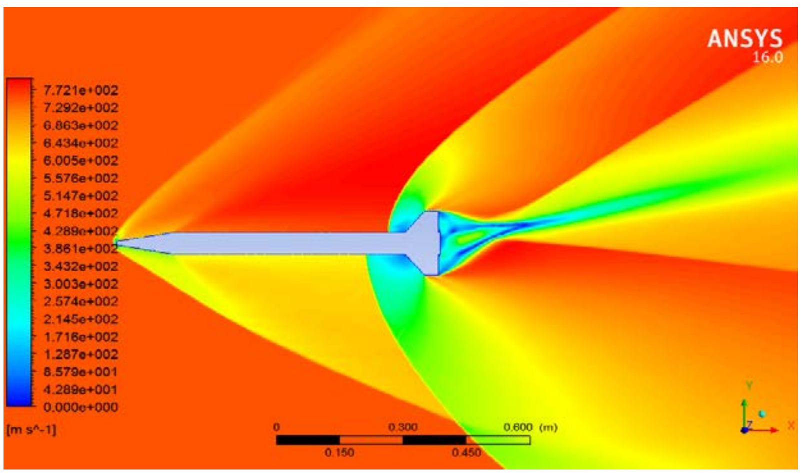
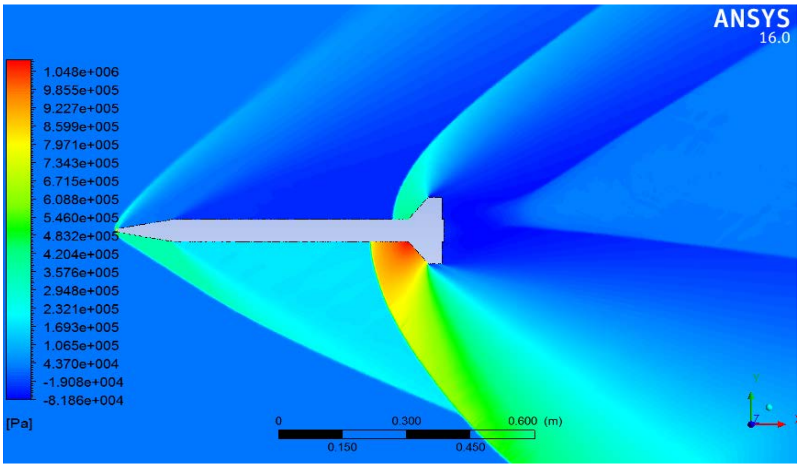
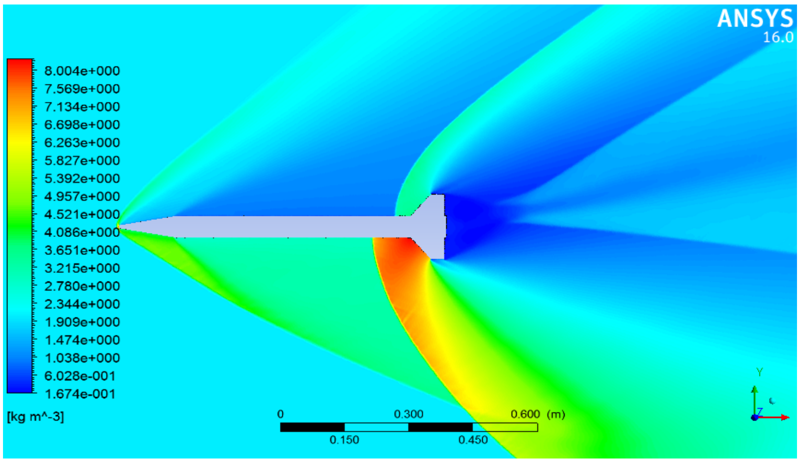
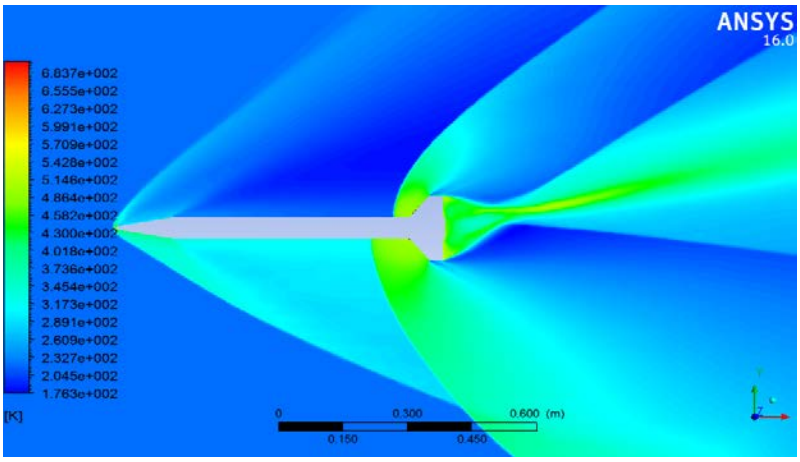
Fig. 12	0^o	Density	
Fig. 13	0^o	Temperature	
Fig. 14	12^o	Velocity	

Fig. 15	12^o	Pressure	
Fig. 16	12^o	Density	
Fig. 17	12^o	Temperature	

4.2. Geometry and Meshing

The boundary made around the missile body [1] was a C-Domain with standard domain dimensions used in most of the research papers. But the domain used in the analysis was a rectangular domain due to incorrect results obtained in the C-Domain due to the improper shock formation at the curved edge due to hypersonic speeds and also the computational time was reduced in a rectangular domain. Also, the meshing used refinement instead of inflation, unlike the reference paper as it yielded better mesh quality.

4.3. Validation

The comparison of the C_L and C_D for the missile at the reference angle of attack of 6.05^o between their values as mentioned in [1] and the calculated ones are listed as follows in Table 1.

Table 1. comparison between reference paper & obtained numerical values of C_L & C_D

	Mach Number	Angle of Attack (α)	C_L	C_D
Reference Paper Values	2.5	6.05^o	1.011	0.5875
Obtained Numerical Values	2.5	6.05^o	0.9665	0.6157

A series of analysis were carried out with angle of attack ranging from 0^o to 12^o whose theoretical values of C_L and C_D were calculated using linear interpolation between Angle of attack and C_L, C_D values from their existing values at 6.05^o. The numerical values of C_L and C_D were also calculated on ANSYS at these angles. The results are stated in Table 2.

With an increment in the value of angle of attack from 0^o to 12^o, it was found that both the numerical C_L and C_D values increased.

Table 2. Variation of C_L & C_D with Angle of Attack (α)

Mach Number	Angle of Attack (α)	C_L (Theoretical)	C_L (Numerical)	C_D(Theoretical)	C_D(Numerical)
2.5	0	0	0.04	0.3979	0.3799
2.5	1	0.1173	0.1222	0.4242	0.4064
2.5	2	0.2943	0.3075	0.4526	0.4340
2.5	3	0.4712	0.4938	0.4827	0.4614
2.5	4	0.6482	0.6793	0.5148	0.5354
2.5	5	0.8251	0.8655	0.5491	0.5721
2.5	6	1.002	1.0470	0.5856	0.5598
2.5	7	1.1791	1.1319	0.6245	0.5976
2.5	8	1.3560	1.4224	0.6660	0.6374
2.5	9	1.5331	1.4656	0.7103	0.7429
2.5	10	1.7099	1.7851	0.7575	0.7903
2.5	11	1.8869	1.9699	0.8079	0.7699
2.5	12	2.0639	2.1506	0.8616	0.8271

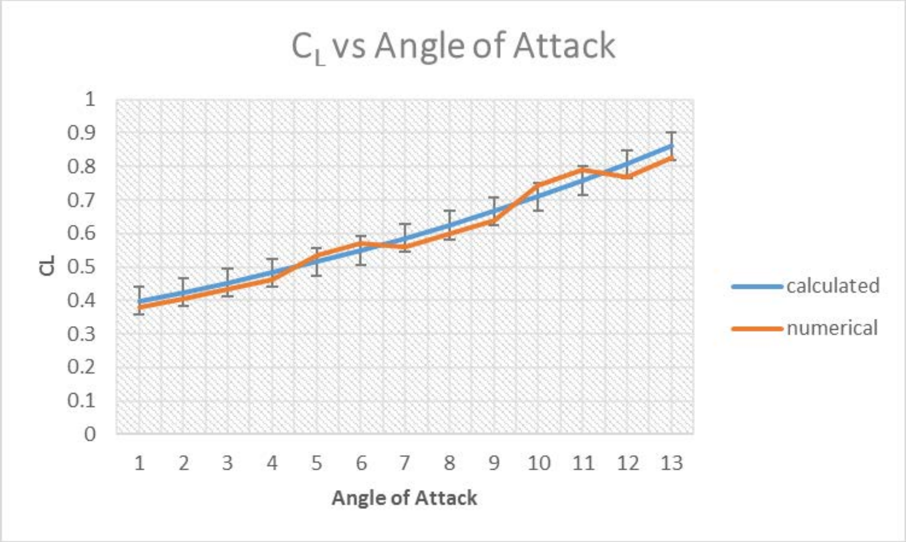


Figure 18. Plot of variation of numerical values of C_L with Angle of Attack

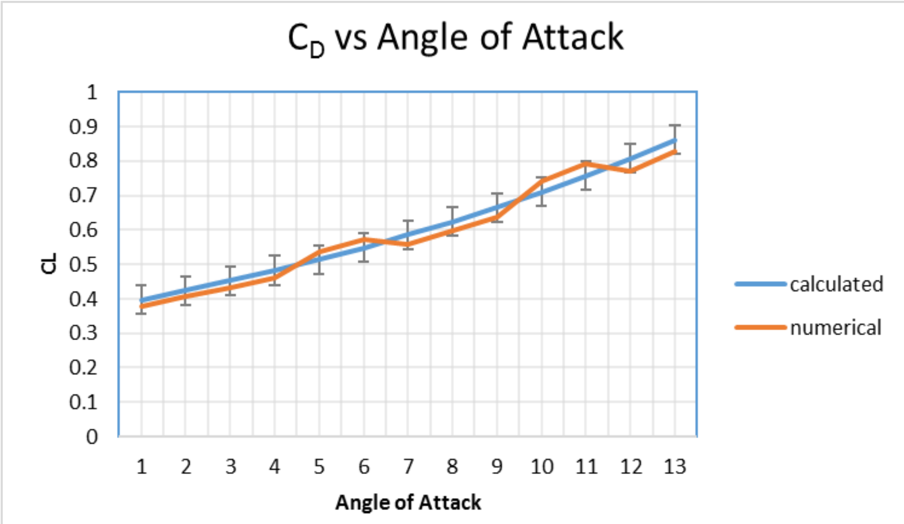


Figure 19. Plot of variation of numerical values of C_D with Angle of Attack

The numerical values of C_L and C_D obtained from the numerical analysis performed were in close agreement with the calculated values as shown in fig 18 and 19.

5. Conclusions

From the numerical flow analysis over a Supersonic missile carried out on ANSYS Fluent to optimize the C_L/C_D ratio by varying the angle of attack while keeping the Mach number same, it was found that the angle of attack giving the maximum C_L is 12^o with a CL value of 2.15058 and with a maximum C_L/C_D ratio of 2.5.

As per the validation done using the results obtained from the analysis and the reference paper values, it was observed that the C_L and C_D values hold close agreement with each other within an error percentage of 4% to 5%.

The shock waves formed due to the supersonic flow resulted in the decrease of the flow parameters such as velocity and Mach number, whereas increase in pressure, temperature and density values behind the shock wave.

With the increase in angle of attack, the shock waves generated become more intense and stronger and the flow separation at the end of the missile body also increases.

Increase in the C_D value was found with increase in angle of attack from 0^o to 12^o which implied that the turbulence of the flow increase with angle of attack.

The maximum velocity obtained at the exit of the missile body also increased from angle of 0^o to 12^o. Hence the aerodynamics efficiency of the missile, in the form maximum C_L/C_D ratio was found to be maximum at an angle of attack of 12^o and hence it was inferred that the efficiency increases with increase in angle of attack of the missile.

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Aircraft Fuselage Recent Developments - A Review

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Abstract Over multiple iterations spanning many years of research a stable and aerodynamically workable fuselage structure has been zeroed down on. The fuselage being the segment holding the passengers and crew requires an immaculate degree of stability during takeoff, landing and flight. Aerodynamic optimisation presupposes every notion of this 'in flight stability'. The recent interest taken in the field of stability under unforeseen air conditions has led to remarkable developments in the field of aerodynamics. This paper attempts to categorically classify these interests into 3 sections- Theoretical, Experimental and Numerical. Various mathematical models and algorithms have been created to study and test the stability of the fuselage under turbulent conditions caused by weather. Turbulence caused by on flight equipment (propellers etc) and methods for its mitigation have also been mentioned. The chine angle analysis of the fuselage reveals that a sharper angle is more favorable in increasing the lift. The study of asymmetrical vortices and its evolution has enhanced the field of aerodynamic optimization. Unconventional aircraft designs like the BWB are studied and compared against the incumbent structures. Various modeling softwares like CATIA have extensively been used to design these structures. A compilation of these recent developments has been presented to those attempting to intensively analyse and study the field of aerodynamic stability.

Keywords Aircraft Fuselage, Analysis, Aviation industry

1. Introduction

The race to develop the most commercially successful and renowned passenger aircraft has shifted gears to focus on research topics closely pertaining to the fuselage. The fuselage is the most recognisable component of the aircraft and it refers to the long hollow tube which encloses the cargo and passengers along with the crew of the plane. The fuselage forms the center piece around which the aircraft structure is built. The fuselage structure has had to adapt with the changing times and working specifications, resulting in four major types – Truss structure, Geodesic construction, Monocoque shell, and Semi-monocoque fuselage. The more commonly adapted method of construction utilized is the Semi-monocoque fuselage owing to its ease of reproducibility in the manufacturing process and ease of working with metals. The general structure of the fuselage varies based on application and prerequisites in the working conditions of the aircraft.

Each aircraft is required to adhere to rigorous regulations, reiterating its ability to come out of worst-case scenarios unscathed, which is attributed to the structural integrity of the fuselage. The gains (loss of weight) made by design alterations to the blueprint of the fuselage, by integrating new age composite materials and changing the fundamental structural design, cannot be at the cost of structural integrity of the fuselage, putting the safety of the aircraft in jeopardy. The fuel consumption of the aircraft is inordinately dependent on its aerodynamic performance through the air. Aerodynamics of the aircraft plays a crucial role in efficiently developing lift without exponentially increasing drag. The aerodynamic design is an aspect that is heavily taken into consideration in the initial stages of the design process. Various additions made to the fuselage over the years has handed the pilot greater control over the plane. The ability of the aircraft to follow the computed trajectory through the 3 phases of flight, and the relatively low latency in reaching equilibrium after hitting disturbances in the air is in part due to the stability of the aircraft. Based on the preconditions, the manoeuvrability and versatility of flight actions can be crafted by altering the stability levels of the fuselage specific to the aircraft model.

Data along various parameters, like the global passenger trips and accessibility to air travel in developing countries, see an exponential increase over the past decade with this development to continue in years to come, indicating a greater proliferation and demand for air travel. Seeking to capitalise on this opportunity, the bigger players in the field of aeronautics have made a major push towards reducing the cost incurred by the passenger. This in tandem with increasingly stringent environmental standards has set the future trend for fuselage design to accommodate aircrafts that have a smaller environmental footprint along with increased seating capacity and shorter travel times without compromising on comfort and safety. This implies that fuselage will have to withstand forces at supersonic flight, consist of materials made of lighter and yet stronger composite materials and undergo a transformation in the design philosophy. Plans to make the fuselage structures smarter by incorporating health monitoring and fault tolerant mechanism and more robust flight control systems are in the works. Attempts to improve aerodynamic efficiency by means of active flow control systems are also being taken in consideration. In an attempt to improve the optimization process of the fuselage design, three main characteristics are taken into consideration –Structure, Aerodynamics and stability.

2. Literature Review

2.1. Theoretical Analysis of Aircraft Fuselage

Yii-Mei Huang et al [1]tackles the technique of passive sound management systems. Their main objective was to design dynamic dampening absorbers to eliminate fuselage vibrations generated from external influences like propellers etc. They evaluated the appropriate parameters to be chosen in design process of the absorbers, to optimally keep the vibrations and noise generated it a minimum. They primarily constructed mathematical algorithms for the motion, vibrations, interior sound field and the external forces that affect the cylindrical fuselage. These were further used to determine the optimal design and placement of the absorbers. By considering kinetic energy and potential energy of the fuselage and the sound field as objective functions, they concluded that their approach had a major impact in reducing the undesirable noise in the fuselage structure.

ParthaDey et al [2] understands the stability of composite skew plates when subjected to loads. The dynamic stability of composite skew plates was analyzed using four-noded shear flexible quadrilateral plate. Finite element equations of the plate were formulated. Gaussian integration rule was used to calculate matrices for elemental mass and linear-geometric stiffness. First and second order dynamic instability boundaries were then identified. The identified principal stability region was four times the secondary instable region. As load amplitude increased, the first and the second order approximations differed. Region of instability increased with the increase in skew angle. The paper lays out the influence skew angle, lay-up and static in plane loads have on dynamic stability.

Zhiquan LI et al [3], with previous research on tiltrotors as a basis, intended to construct a full-span model tiltrotor followed by its analysis along the parameter of aeroelastic stability in flight. They also established the differences between a semi and a full span model and nailed down the reasons for its instability and monitored the effects of external structures on its aeroelastic stability. After constructing a theoretical model of the tiltrotor, they constructed algorithms to represent various structures and features of the tiltrotor. These equations were used to validate the various parameters, and the results indicated that elastic blades invariably led to more instability than rigid winged aircrafts did, and when these were coupled with fuselage motions, the instability was found to have increased further.

Natural laminar flows (NLF) wings are capable of maintaining flow under laminar conditions over relatively large portions of wing surface. But imperfections produced during the manufacturing process (groves between joints and fixtures) have an adverse effect on aerodynamic performance due to a disruption in air flow over the wing surface. JesúsGaricano-Mena et al [4] studied the stability characteristics of NLF wings in the presence of these indentations. The main objective was to quantify the impact on linear stability under varying degrees of indentation of depth and Mach number. They first established a baseline test under ideal circumstances, and then observed the modifications made to this data when exposed to a perturbation in the surface of the wing structure. They also noted spatial evolution of individual structural elements along the direction of the flow along the amplification factors. They utilized global temporal stability analysis to make these determinations. The results from the test indicated that an increase in grove depth drastically impacted temporal stability which was intensified at higher Mach numbers. They cautioned that these parameters need to be taken into considerations during the design and manufacturing process of NLF wings.

Liang QU et al [5] studied the stability values for the working parameters (angle of attack and sideslip, yaw, pitch and roll rate) of the aircraft under icing conditions. Apart from increasing the weight of the aircraft, icing also decreases the performance of the aircraft. Stable and unstable equilibrium points for stability of the aircraft were obtained by solving the kinematic equations. The stability region was then obtained by using these equilibrium points in a Jacobi Matrix and solving it. An iced aircraft was in steady state if the angle of attack laid below 25.8 degrees (38.7 degrees for an un-iced vehicle). Time domain simulations carried out validated the stability regions obtained. The stability region provided a working region for the aircraft for safe operation.

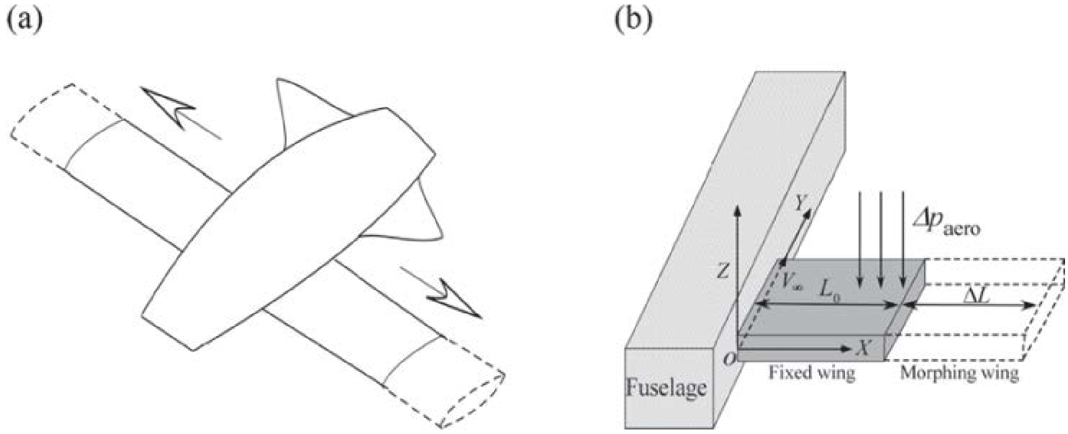

Figure 1. The schematic diagram of morphing aircraft (a) a morphing aircraft with variable-span wings, (b) the simplified model of axially moving wing. [6]

Wencheng Li et al [6] intended to make headway in morphing aircraft design by devising a strategy to suppress the flutter that occurs beyond a certain span length. The rough schematic of a morphing plane is given in figure 1. The three main objectives are, to establish equations for an axially moving cantilever kept in supersonic fluid, second, to develop a new strategy for flutter control, and to obtain the boundary conditions for morphing rate by slowing varying the system. After constructing the structural model of the aircraft, it was put through a set of numerical simulations which controlled the rate at which the cantilever plate was extended and retracted, exposing it to varying degrees of aerodynamic loads. They concluded from the results that the speed of the flutter was inversely connected to the span length and it also increased with increase in deploying rates. They suggested that this problem could be overcome by strategically varying the span length along with proper amplitude to improve the quality of flight of the aircraft.

N. Siepenkötter et al [7] considers the nonlinearity of a flexible aircraft and studies its stability. Nonlinear effects on stability need to be considered along with frequency and damping of motion. Eigenvalue analysis incorporates the nonlinear characteristics while modelling motion. The flexible aircraft is modelled using Newton-Euler equations. Forces acting due to air were modelled using strip theory. Stability regions on the system were found beyond the known equilibrium points. The obtained equilibrium values spoke of a trimmed aircraft moving at 100m/s. Eigen values obtained were used to identify 9 forms of motion and determine the stability under them. The above modelling can be used to study flexible aircrafts in unsteady aerodynamic conditions as well.

3. Experimental Analysis of Aircraft Fuselage

Active noise control systems have the unfortunate effect of amplifying the vibrations in certain regions of the fuselage. C. Natale et al [8] attempted to tackle this problem by conducting an experimental analysis of an active vibration control system on a fuselage panel of BOEING 717 aircraft. The main objective was to construct a mathematical model which is representative of the fuselage, and thereafter to validate the algorithms effectiveness as a tool in the design process experimentally. The experimental setup included a panel along with actuators rated to produce a force of 133N and a maximum stroke of 60 micro meters. The results predicted by the algorithm closely resembled the experimental results and hence the authors concluded that they were successful in demonstrating the feasibility of their approach.

Robert M. Hall et al [9] inspects the stability of chinned aircrafts with different cross-sectional fuselage area. He calculated the pitching, yawing and rolling moment for these sections at different angles of attack and sideslip. Two fuselage sections of chine angles 30 and 100 degrees were subjected to winds in the upright and inverted configurations. 276 sensors placed around the body of the aircraft picked up the instantaneous pressure at different angles of attack. The data collected revealed that sharper chines resulted in larger lift coefficients and greater longitudinal stability. Upright configurations exhibited more stability than inverted ones.

Wen Jing et al [10] investigates the static directional stability of an aircraft at different angles of attack. The part of the aircraft contributing most to the instability was primarily identified and then probed into. A model of the aircraft consisting of 194 pressure taps was subjected to winds of 35m/s at angles of attack ranging from 0 to 46 degrees under the influence of sideslip. The vortices and their flow were extensively studied at the vertical tail and the fuselage body. The net effect of the yawing moment and windward leeward pressure difference verses stability at different attack- sideslip angles was recorded. It was noted that maximum instability was caused by the vertical tail and the fuselage body. The stability at the tail increased when the windward vortex completely broke down. Instability in the middle of the fuselage rapidly increased with an increase in angle of attack.

T.P. Ratvask et al [11] investigated the effects of icing on aircraft stability and control. For this purpose, a DH-6 Twin Otter aircraft was considered. The aircraft was tested in the normal as well as in iced conditions (Styrofoam attached to horizontal and vertical stabilizers). The aircraft was flown with 3 different thrust coefficients (0.14, 0.07, 0.00), to determine the power effect (engine torque and power coefficient etc.). Maximum Likelihood algorithm was used to analyse the extensive data collected on flight manoeuvres. Modified Stepwise Regression method was then used to obtain stability. Static stability decreased by 10% due to tail ice. A drastic decrease was seen in directional stability during the zero-thrust case. Yaw damping and pitch damping remained unaffected.

Fabrizio Nicolosi et al [12] wrote a comprehensive analysis on the Tecnam P2006T a four-seater twin propeller aircraft during its flight. Flight quality was assessed, and stability derivatives were determined using longitudinal parameter estimation techniques. The above aircraft designed by Luigi Pascale was subjected to real time flight test, after its scaled model had been subjected to extensive testing in the wind tunnel. Static-dynamic lateral and longitudinal stability assessment of the aircraft was carried out by subjecting the aircraft to a number of flight maneuvers. Parameter estimation during flight was done using the Maximum Likelihood Method. The wind tunnel and full-scale test coincided with little discrepancy. The frequency response during the maneuvers fell well within the thumbprint criterion. The aircraft designed was successfully tested.

Fabrizio Nicolosi et al [13] tested a scaled model of the Tecnam P2012 in a wind tunnel and compared the values obtained to those obtained by CFD analysis. Estimating the lateral and longitudinal stability was the primary objective. The model fitted with strain gauge balances and was subjected to winds of 40m/s. The effect of the flap on longitudinal stability and lift was extensively tested along with the effects of the horizontal tail. Lateral directional stability was also looked into. A CFD analysis looks into the wing span loading and drag breakdown along with the analysis of those mentioned above. The neutral point of the aircraft shifts by 3% with full flap deflection at zero angle of attack. It was also seen that the winglets and nacelles caused maximum drag. The pressure variations on the Tecnam P2012 are shown in figure 2. The Results obtained were used for the final design of the aircraft

Masoud Mirzaei et al [14] computed the drag due to the aft body of a cargo aircraft. A scaled modified model of the passenger jet was subjected to streams of air in a single return wind tunnel at angles of attack between -10 to 20 degrees. Numerical models of 4 modified aft created from an optimised prototype were subjected to 2 simulations (Spalart–Allmaras (SA) modelling and Large Eddy Simulation (LES): more computational effort). The LES model proved to be more accurate (as compared to the wind tunnel model) than the SA. The cargo vehicle saw considerable increase in drag coefficient (28%) due to flow separation near the ramp door. Further optimisation led to the decrease in drag coefficient.

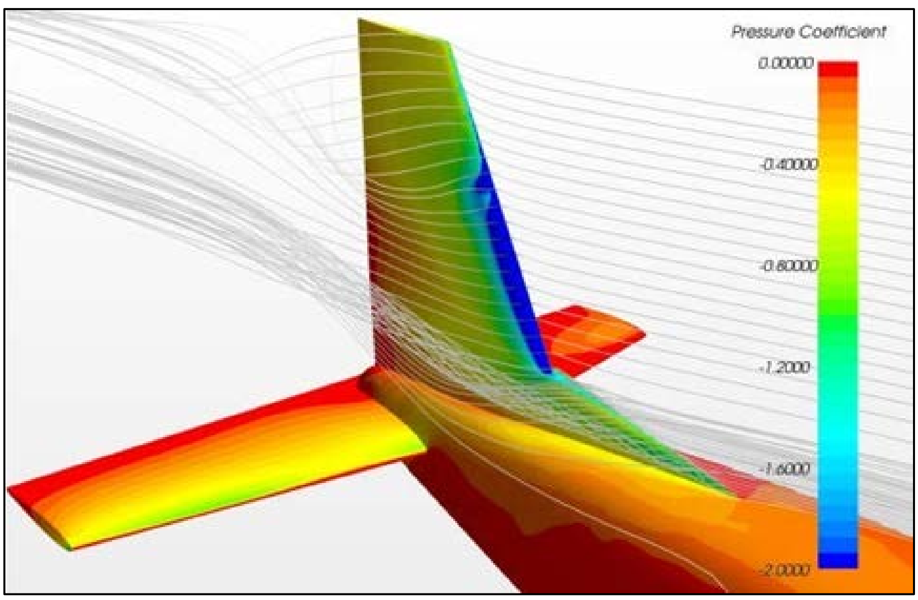

Figure 2. CFD analysis of the vortices on Tecnam P2012 [13]

DENG Xueying et al [15] studied the flow of asymmetric vortices over a slender body at high angles of attack. Mechanisms of vortices were studied and its evolution due to perturbations on the nose was presented. The evolution of a vortex from a symmetric to an asymmetric state was looked into using slender bodies of different nose shapes. To prove that the non-determinacy of the asymmetric vortices was due to the non-determinacy of the perturbation, a model was subjected to two different wind stations. Side forces acting were being measured in order to correlate it with asymmetric vortex flow. Active control of forebody vortices was also looked into. The behaviour of the asymmetric vortices was controlled mainly due to the irregularities on the nose. The findings of this paper are many and can be widely used in fields of aerodynamic optimisation and design.

Shi Wei et al [16] analyses the behaviour of vortices over the chinned fuselage when subjected to different angles of attack. A scaled down model of the fuselage section is bombarded with winds of 35 m/s at different angles of attack and side forces are measured. Artificial tip perturbations are introduced on the nose at different circumferential angles. Pressure taps measure the variation in pressure at 22 different circumferential nodes. With the variation in the angle of attack between 0 to 70 degrees the vortices morph from symmetric to asymmetric and finally they breakdown. The nature of the asymmetric vortices is determined. The vortices on the side of the distortion are higher than the ones on the opposite side. This results in a side force acting towards the lower vortex. A conclusive idea of the vortices acting on the windward and leeward side is established.

4. Numerical Analysis of Aircraft Fuselage

S. Dey et al [17] devised a set of experiments through which a comprehensive account of the behaviour of doubly curved composite shells when exposed to various time varying loads. The input parameters chosen were ply-orientation angle, radius of curvatures, material properties, dynamic and static loads etc within appropriate constraints. The moving least square method in tandem with original Monte carlo simulation method and finite element modelling were used to mathematically derive and validate the results. They concluded that a variability of the input parameters like aspect ratio, ply orientation angle and radius of curvature had an impact on the structural instability of the composite panels and should be a prevalent factor during the design and manufacturing process of the panels.

C. Suresh et al [18] delves into the history of aircrafts and describes the various attempts to increase the lift by utilizing bi or even tri wing concepts. But due to their high inefficiencies, a C-type mono-wing design was settled for. The instrumental parameter to be considered during wing design is the lift to drag ratio, and the main aim of their work was to definitively prove that the C-wing design is considerably better with respect to a straight wing design with the same surface wing area across a wide range of operational flight speeds and angles of attack. The main objective is to conduct a comparative aerodynamic performance study along the parameters of drag, lift and stall using CFD analysis. The three-dimensional model of the wing designs was made using CATIA and ANSYS CFX softwares. The post processing results indicate a superior performance and lift to drag ratios over a wide range of angle of attacks for the non-planer C-wing design over the plane wing design.

Cristofaro M et al [19] attempted to generate an aerodynamic data which would form the baseline for the simulation of a reginal jet aircraft which could be used to check the performance and aerodynamic stability of the jet. Aerodynamic models were not only confined to CFD analysis, but also included semi-empirical approaches which utilized data from wind tunnel tests to validate the results generated from the simulations. A baseline geometry was first established from which the impacts of changes in the geometry of the aircraft could be compared to. They noticed that a change in the wing sweep angle had a bigger impact on the stability than the wing aspect ratio of the aircraft. An increase in the sweep angle led to an increase in the angle of attack which in turn led to a negative elevator deflection to trim the aircraft. They indicated that any future work would further improve on the dataset to optimally refine the aircraft geometry and demonstrate the ability of CFD analysis to design aircraft geometry.

YongxiLyu et al [20] attempted to construct and design a control law under unsteady aerodynamics. They utilized Extreme Learning Machine (ELM), and to build the algorithms, the authors made use of backstepping and daisy chain control allocation. The model around which the equations and simulations are conducted is an advanced fighter with blended wings, leading to edge flaps and trailing flaps which are distributed along the X axis of the body in a mirror image fashion. A wind tunnel test is conducted which is used as reference against which the designed control low is validated. The results indicate that The ELM model describing the unsteady aerodynamics showed promising fidelity to the data from the wind tunnel test. The authors concluded that the model had accomplished to accurately represent the aerodynamic forces experienced by the fighter jet under normal and unsteady conditions. They successfully show that a control law designed by combing Radial Basis Function (RBF) network and the Dynamic Surface Control (DSC) method is instrumental in solving unsteady aerodynamic problem statements.

Juhee Lee [21] performed a computational analysis with an optimized wing structure in an attempt to construct a three-dimensional WIG aircraft consisting of a fuselage and a wing with a reduced horizontal tail which is normally necessary to counteract the vibrations and offer stability but is detrimental to static stability when ground effects are not in play. They first constructed a mathematical model describing the Wing-In-Ground (WIG) model. This model, in two configurations, wings with and without ground effects, were validated using CFDc analysis followed by flow analysis which utilized three-dimensional Navier-Stokes equations. In total, six stability configurations were evaluated like, static height stability, varying locations for the center of gravity, varying degrees of trim for flight underground effects etc. From the results, they concluded that the optimised wings offer improved aerodynamic performance. They also deduced that to achieve higher stability, ideally the tail should be placed higher than that was considered in this study and to satisfy the stability requirements, a tail wing one-fourth the size of the main wing area was required.

The BWB Aircraft is more susceptible to turbulent airflows due to the lack of a vertical tail. Sami Ammar et al [22] therefore performed a stability analysis on a 200 passenger self-designed BWB and compares the results to an equivalent conventional A320 and B747 airbus. CEASIOM a designing platform was used for conceptualizing the BWB under parameters like drag and engine performance. CATIA was later used for the completely optimized modelling. Performance and stability of the above vehicles were analyzed under similar conditions. Performance analysis indicated reduction in take-off weight and distance with improved lift drag ratio for the BWB. Stability analysis indicated instability along the lateral axis of BWB during Dutch Roll because of low damping ratio.

Toshihiro Ikeda et al [23] explores the aerodynamics of a BWB Aircraft design. A new configuration for ferrying passengers was analysed and presented as a viable alternative to the traditional discrete fuselage wings structure. Certain parameters like load to drag ratio, weight of the BWB and the passenger capacity, were used to design (using CATIA V5, FLUENT 6.2 softwares) and optimise (CFD analysis) the vehicle. NASA's inventory of research on BWB was optimised and used to carter to the needs of the authors design. The optimised BWB created turbulent eddies, which couldn't be resolved. The load to drag ratio achieved by the BWB was 1.4 times greater than that of a regular aircraft. Noise emission of the BWB reduced due to smaller drag values and lesser engine thrust requirements. The BWB with its increasing advantages seems to be the vehicle for the future.

Moving Surafce Boundary-layer Control (MSBC) is a fringe idea which could be utilized to improve the aerodynamic performance of any wing owing to its ability to delay the separation of boundary layer of airflow from the surface of the aero foil. One configuration through which this is implemented is by attaching a rotating cylinder rotating counter to the direction of the airflow. Abdus Salam et al [24] utilizes this concept and envisages the design of a wing with circle at its leading edge and investigates the gain in aerodynamic performance under varying circumstances along a range of angles of attack. They chose to modify a NACA-0010 model airfoil so as to satisfy the requirements of this experiment and built a 3-D model of the design. The results from the computational analysis indicated an increase in the lift component of the airfoil by 13.75 percent at the detriment of increased drag due to increased friction. The authors remarked that the benefits offered substantiated measures to reduce the drag produced through structural modifications like tapers, winglets etc.

Flutter is an unfavorable consequence of unsteady aerodynamic and elastic forces acting on an aircraft during the act of flying, and in extreme conditions can lead to catastrophic failure. Y. J. Choia et al [25] tackled this phenomenon in T-tail among transport aircrafts by conducting an empennage flutter analysis under the event of a modification in the fuselage length due to plug-in segments. They devised an experiment where two models were constructed using FEM, one acting as a base test and the other model with 120 inches added to the fuselage length acting as the plug-in segment. They used MSC.NASTRAN to check parameters like stiffness, mass distribution and aerodynamics. They first conducted a normal modal analysis acting as the reference against which data would be cross verified. This was followed by the flutter analysis test. Upon going through the results, they concluded that the addition of the plug-in reduced the empennage flutter mode but was found to have an adverse effect on complex flutter mode for wing and the empennage section.

C. Edward Lan et al [26] used Fuzzy-Logic (FL) to understand the aerodynamic effect during landing. In the period of touchdown, air around the aircrafts collapses into a more complex unstable form which causes hard landings and runway veer-offs. The flight variables during descent were used to generate the possible stability and control derivatives which were used in computing the overall stability using FL inversion. The stability values generated, synchronised with those obtained from a Flight Data Recorder on a twin jet transport aircraft. It was noticed that roll controls while landing were very much different from those experienced during flight. The control over the rudder to avoid veer-off was decreased due to the turbulent air and strong cross winds. Air is noticed to behave very differently during landings.

Zhenlong Wu et al [27] explored the lateral stability of an aircraft under heavy rain. A DHC-6 Twin Otter aircraft was subjected to numerical simulation and aerodynamic coefficients during rain were obtained using Eulerian-Lagrangian method. Strip theory and linear fitting processing was used to procure static and dynamic derivatives. Controllability of the aircraft was tested by analyzing its response to unit step changes in the control surface. The numerically obtained values for lift and drag were in harmony with those obtained experimentally. Of the 13 coefficients considered for lateral stability only four showed significant changes during rain, contributing to most of the instability experienced. Heavy rainfall adversely affected recovery of stability during Dutch roll mode, also increasing the time for recovery. The potency of the rudder and the aileron also reduced. Heavy rain decreases stability and controllability thereby increasing the chances of flight failure.

IlhanTuzcu et al [28] analysed the stability of a flexible aircraft due to flight dynamics and that due to aero-elasticity. An aircraft was first modelled such that the wings, fuselage and empennage could be distinctly identified. Unified formulation (UF), Flight dynamics of the quasi-rigid aircraft (QR), Aero-elasticity of flexible components (AF) and Aero-elasticity of restrained flexible aircraft (AR) were the four frameworks then used in studying the models stability. Divergence and flutter speed were obtained under UF. Greater speeds resulted in negative stiffness and divergence, as the AF revealed. Cause of flutter was aerodynamic forces shown in the AR model. An analysis on the business jet showed that the most accurate model for closed loop control was the Unrestrained Aircraft one.

J. Mieloszyk et al [29] demonstrate the proficiency of computational power and constrained optimization in the efficient designing of an aircraft. The main objective of the research was to improve and expand preexisting models encompassing the whole aircraft. They decided to apply the optimization loop to a boxwinged aircraft along the parameters of aerodynamics, structure and dynamic stability with parameter specific constraints. The results of the optimization algorithms point to a better lift and optimal air flow aerodynamically, a change in the geometry to attain structural stability and reduced oscillations over wide tested airspeeds and altitudes. The results of the pressure simulations are present in figure 3. The authors concluded that they were successful in effectively running and implementing the results of the constrained optimization problems to create the most efficient design despite of its unconventional nature. Though the pilot raised concerns regarding the limitations of the aircrafts handling capabilities, they believe that these minor grievances would be ironed out with further iterations.

Viken N. Koukounain et al [30], devised a series of experiments to study the vibro-acoustic response resulting in the change in thickness of the fuselage panel skin. The main objective was to develop reproducible semi-empirical procedure to hypothesize the dynamic response with certainty when under the turbulent boundary layer (TBL) excitation and the subsequent noise within the fuselage structure brought upon by vibrating fuselage skin. This TBL condition occurs when the aircraft is cruising at high altitudes. The experiments conducted were in line with international standards set by aviation bodies so as to be compliant with regulations.

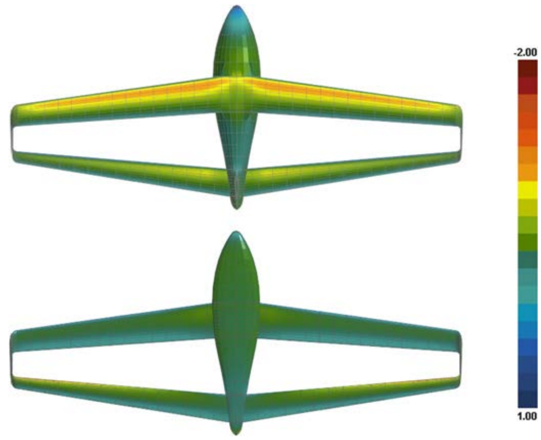

Figure 3. Pressure coefficient distribution for cruise conditions on the optimized aircraft. (Refer paper for further explanation regarding the colour gradient) [29]

From several parameters along which the phenomenon could be studied, sound pressure and transmission loss were chosen. Various external factors (dampening, flanking etc) affecting the efficacy of the data were taken into considerations in the algorithms and the final results were in line with experimental data. Hence the authors concluded that their approach was a low-cost way to better design fuselage structures in order to attenuate the vibrations generated due to various phenomena.

5. Summary of Literature Review

Permutation and combinations of many current theories and formulas have been pivotal in establishing new ground-breaking concepts in the recent past. Reshaping the fuselage into an elliptical structure proves more beneficial for the overall stability of the aircraft. Drag Reduction using new established algorithms proves more efficient. An optimisation algorithm was also generated for an aircraft in stormy weather conditions. The theoretical conceptualisation of new concepts has required a great amount of testing before finally being adapted into the aircraft. These theories are first validated by means of physical experiments or by the use of numerical software, before finally being implemented.

The success of every in- flight aircraft can be mapped back to the arduous hours dedicated by a delegation, tweaking the parameters of a wind tunnel. The indispensability of a wind tunnel is further established in this day and age, even with the presence of simulations involving Computational Fluid Dynamics (CFD). Stability under icing conditions is looked into and compiled from tests in the tunnels. Fuselage panels with all its composite variants are tested for structural stability. The introduction of perturbations to the nose of the aircraft and its effects on the vortices around the aircraft body are extensively tested

6. Conclusions

The relentless pursuit of improved performance has pushed the boundaries of aircraft design, forever changing the face of the aeronautics and aviation. The advancements made in subsidiary industries and sciences have demanded the fuselage to adapt with the times. This has seen a marked increase in the intensity of research conducted concerning unorthodox fuselage designs. This has inevitably led to challenges arising in the department of aerodynamics and stability. The field in general has resorted to unconventional solutions which require intense computational verification in tandem with real life experimentation. Some of the design philosophies tackled here are, boxwinged aircraft, BWD's, MSBC's etc. These concepts theoretically offer a more efficient solution to the problems faced by the aircraft industry today. The analyses of the stability of these fuselage designs were conducted on miniature models in wing tunnels and using simulation technologies. Great strides were also taken in further refining modern day wing and fuselage designs, subjecting them to a wide range of circumstances, ensuring their legality in line with aviation regulations. Various constructs to increase the stability were also addressed and required further experiments to be conducted to realise the true potential of these technologies.

Fuselage technologies are on the verge of experiencing revolutionary changes with ideas on the fringes finally taking center stage. These investments are bound to come to fruition with these aircrafts capable of transporting more with relatively lower fuel consumption and a smaller environmental footprint. All the technologies worked on in these papers require further experimentation and ideation for them to become more main-stream.

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Recent Developments of an Aircraft Fuselage along Theoretical, Experimental and Numerical Approach - A Review

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Abstract Expressed in nature's infinite subtleties, the Fuselage draws its inspiration from the streamlined body of a bird or a fish, channelizing the flow of air around, enabling its ease in flight. Spanning most of the aircrafts structure, it plays a crucial role in the ferrying of people and cargo, simultaneously balancing the shears due to the empennage and wing structures all in mid-air. Its structural integrity is often questioned by failures due to load or bad air during maneuvers, causing instability which has led many to intensively explore and develop an ideal fuselage. The behaviour of the fuselage is crucially determined by the structural integrity and aerodynamic performance. This paper is an attempt at collating the recent technological advances pertaining to the fuselage. We've streamlined and categorised the wide-ranging scholarly articles by three fundamentally varying approaches - Theoretical, Experimental and Numerical. The theoretical approach saw the authors test out their hypothesis by utilizing and constructing various mathematical models using scientific principles with no verification by actual experimentation or simulation work. The experimental approach pertains to those papers whose authors devised experiments, whose data was used to draw distinct conclusions. The numerical approach mainly dealt with heavy computational analysis using FEM and CFD analysis. Therefore, this paper serves as a compendium for researchers and developers attempting to familiarise themselves with the current advancements and developments in domain of fuselage technology.

Keywords Fuselage, Performance, Analysis, Aircraft

1. Introduction

The race to develop the most commercially successful and renowned passenger aircraft has shifted gears to focus on research topics closely pertaining to the fuselage. The fuselage is the most recognizable component of the aircraft and it refers to the long hollow tube which encloses the cargo and passengers along with the crew of the plane. The fuselage forms the center piece around which the aircraft structure is built. The fuselage structure has had to adapt with the changing times and working specifications, resulting in four major types – Truss structure, Geodesic construction, Monocoque shell, and Semi-monocoque fuselage. The more commonly adapted method of construction utilized is the Semi-monocoque fuselage, owing to its ease of reproducibility in the manufacturing process and ease of working with metals. The general structure of the fuselage varies based on application and prerequisites in the working conditions of the aircraft.

Each aircraft is required to adhere to rigorous regulations, reiterating its ability to come out of worst-case scenarios unscathed, which is attributed to the structural integrity of the fuselage. The gains (loss of weight) made by design alterations to the blueprint of the fuselage, by integrating new age composite materials and changing the fundamental structural design, cannot be at the cost of structural integrity of the fuselage, putting the safety of the aircraft in jeopardy. The fuel consumption of the aircraft is inordinately dependent on its aerodynamic performance in flight. Aerodynamics of the aircraft plays a crucial role in efficiently developing lift without exponentially increasing drag. The aerodynamic design is an aspect that is heavily taken into consideration in the initial stages of the design process. The ability of the aircraft to follow the computed trajectory throughout the 3 phases of flight and the relatively low latency in reaching equilibrium after hitting disturbances in the air are in part due to the aerodynamic performance of the aircraft.

Data along various parameters, like global passenger trips and accessibility to air travel in developing countries, see an exponential increase over the past decade, with this trend to continue in years to come, indicating a greater proliferation and demand for air travel. Seeking to capitalise on this opportunity, the bigger players in the field of aeronautics have made a major push towards reducing the cost incurred by the passenger. In tandem with increasingly stringent environmental standards, this has set the future trend for fuselage design to accommodate aircrafts that have a smaller environmental footprint along with increased seating capacity and shorter travel times without compromising on safety. This implies that fuselage will have to withstand forces at supersonic flight, consist of materials made of lighter and yet stronger composite materials and undergo a transformation in the design philosophy. Plans to make the fuselage structures smarter by incorporating health-monitoring and fault-tolerant mechanism and more robust flight control systems are in the works. Attempts to improve aerodynamic efficiency by means of active flow control systems are also being taken into consideration. In an attempt to improve the optimization process of the fuselage design, two main characteristics are taken into consideration –Structure and Aerodynamics.

2. Literature Review

2.1. Theoretical Analysis of Aircraft Fuselage

Yuan Li et al [1] intends on decreasing the errors of displacement between two fixtures of the fuselage as compared to an ideal theoretical model. Errors in displacement of fixtures (error between coordinates along the fixture and its theoretical counterpart) are calculated based on geometric constraints using the Gauss-Newton algorithm. The initial value of the coordinate was obtained. If error above a threshold is present, the coordinates are transformed to new ones by multiplying them with a transform function. After certain iterations if error still persisted, the weightage of each error pertaining to each constraint was changed, and the process was repeated. The algorithm was applied onto coordinates of the fuselage and the errors obtained between the physical and theoretical model were within the required margin. This multi-objective optimization mode which considers constraints performs better than the ones traditionally employed in the field of posture adjustment.

John T. Wang et al [2] identified the need to devise methods which determined the strength of damaged composite fuselage panels, as the preexisting methods did not consider the geometrical nonlinear effects and were tedious to use. The objective of their research was to ascertain the effectiveness of the Resisitance-curve (R-curve) method to predict the residual strength of damaged composite fuselage panels accounting for hoop, axial and pressure loads. The R-curve constructed was used to test the nonlinear behavior and the residual strength of both flat and curved composite cracked plates. All the results were validated with reference to data conducted using two different methods called gradient method and virtual crack closure technique. In the end they concluded that the correlations between the data sets were very similar and that the R-curve method could be used to determine the strength of damaged panels.

Adrien Boulle et al [3] examined the feasibility of using a pressurized elliptical fuselage over a circular one. Three different elliptical fuselage constructs considered were: monolithic (having no core, only facesheet whose thickness varies with polar angle), symmetric (a core encompassed by 2 facesheets both of equal thickness and varying with polar angle) and asymmetric (a core encompassed by 2 facesheets of unequal thickness and varying with polar angle). Volumes of the facesheets were calculated and used as substitutes for the mass. A series of mathematical formulas were used to calculate the tangential force bending moment, and max stress conditions were used as constraints to derive the thickness of the face sheet. A monolithic structure was proved to be less beneficial, whereas the symmetric structure, though better than the monolithic, was structurally underused. The asymmetric structure was proved to be most beneficial, with only 1% weight gains and a lot more available area.

C.Hesse [4] proposed and built a theoretical model that actively attenuates sounds within an enclosed right cylindrical composite fuselage using a series of actuators and sensors integrated into the structure. The main objective was to construct a general mathematical model which was applicable to a wide range of fuselage designs. This system termed as Active Structural Acoustic Control (ASAC) relies on Acoustic Radiation Modes (ARM) to determine the contributions made by the fuselage to internal sound. The mathematical model for the ARMs was constructed by assuming the fuselage to be the main proponent of the disturbance, disregarding support structures. This model was tested on a Finite Element Model (FEM) of a composite fuselage. The tests determined the number of ARMs necessary to effectively represent the sound field and set the limits to which the system would dampen the sound field. They concluded that this would be representative of the dampening effects despite of irregularities that could possibly be found in fuselage structures.

The European research project, Aircraft Wing with Advanced Technology Operation (AWAIATOR), entailed the testing of contraptions called mini Trailing-Edge Devices (mini-TEDs) which were a part of the Multifunctional Control-Surface System. K. Richter et al [5] explored the investigations that were conducted by the AWIATOR team which predominantly revolved around the determination of the impact the mini-TEDs had on the aircraft aerodynamics in various configurations like cruising, takeoff and landing procedures. The authors also intended to monitor the influence of the Reynolds number on the functionality of the mini-TEDs. The experiment followed a path where the numerical and computational tools were first validated with data from wind tunnel tests before they were used to run simulations. DLR-TAU, a code segment in the CFD software, was used to perform the numerical investigation. The tests were conducted on a modified Airbus A340-300 with the mini-TEDs applied to wing trailing-edge, and for a Mach number of 0.82. The determination was made that predictive tools were representative of the behaviour since it matched up with the wind tunnel data. The results from the tests indicated a significant increase in lift coupled with drag reductions under medium to high lift coefficients, implying a net positive effect. The Reynolds number influence showed unreliable results indicating a better integration of the mini-TEDs into the wing structure was required for efficient functioning. Overall, the results showed great promise for the mini-TEDs in improving the aerodynamic efficiency of future aircrafts to come.

Tung Wan et al [6] analyses the change in performance of an aircraft due to heavy rain. Using a new analytical system, Navier-Stokes equation was applied on every triangle generated by modified Bowyer scheme grid generation. Cratering effect of the water layer is considered along with the terminal velocity of the droplet and the air density. It was found that the lift coefficient of an aircraft in rain was greater than that at normal times when the angle of attack was zero. With the increase in angle of attack, the reverse occurred. The stall angle of attack decreased because of downward force exerted by the droplet. Development of a water film was observed to cause more aerodynamic degradation than the density of water in air or the velocity of the droplet.

Pierluigi Della Vecchia et al [7] introduced a new method to evaluate lift characteristics of a transport aircraft. Nasa Blackwell method, where the horse shoe vortex is applied on straight wing elements, was modified. This predicted wing stall characteristics of the flaps in active and retracted condition. A method to compute effect of high lift devices was also established. A maximum lift curve was also computed. The values of lift coefficient obtained for a clean configuration using the new system when collated with those from CFD analysis show discrepancy of less than 5%. The new system is thereby validated.

Trailing vortices created in the wake of an aircraft have detrimental effects hypothetically leading to catastrophic consequences in extreme conditions on oncoming aircrafts. Aziz Al-Mahadin et al [8] aims to determine crucial factors and parameters contributing to incidents caused by these trailing vortices. They go about bringing these correlations by weeding through pilot reports of flight incidents (54 pilot reports in this study) and establish factors that influence vortex interactions. They narrow the possible culprits down to 9 factors – Aircraft model, flight phase, Altitude at which the incident occurred, aircraft mode, response parameters, wind speed and direction, visibility, separation and roll angle vs altitude. The authors recommended that a more standardized reporting structure be established, which worked in tandem with on-flight data and pilot accounts so as to remove subjectivity in case reporting.

Figure 1. Trailing Vortices in the wake of the Airplane [8]

Fabrizio Nicolosi et al [9] strived towards predicting and quantifying the aerodynamics related coefficients acting on the fuselage. New methods for the assertion of drag, yawing moment and pitching moment were established. A turboprop fuselage having 3 segments (nose, cabin, tail) of length 30m and diameter 3.4m was considered as reference, based on which 5 other models were generated by varying one of the three segments. Meshing of the model and creation of atmospheric conditions were done using STAR CAM+ software. Drag coefficients acting were predicted by summing up the individual coefficients obtained at the nose, body and the tail. Pitching moment coefficient and yawning moment coefficients were calculated considering the geometry of each given model. Results obtained using the new paradigm were in correspondence with the ones generated using CFD model. The proposed model highlights the significance of the geometry of the structure in question.

Huang Jiangtao et al [10] propounded the use of neural networks for the aerodynamic optimization of a supercritical wing, hence reducing the drag coefficient. An improvised Back Propagating Neural Network algorithm was developed considering the Mach number. The neural network using an unconventional learning approach generated a testing model akin to a CFD model. The error detected between the CFD and the neural network was minimal. The optimized aircraft wing in contrast with the original one resulted in weaker shock waves. The drag coefficient had also considerably reduced.

3. Experimental Analysis of Aircraft Fuselage

NASA in collaboration with Boeing designed, fabricated and tested a Pultruded Rod Stitched Efficient Unitized Structure (PRSEUS a new age fuselage) fuselage panel and demonstrated its ability to withstand damage in line with regulations, demonstrating relative advantages over its contemporaries. Further building on this work, Andrew Bergan et al [11] attempted to test the damage progression in a curved panel of the same kind under various types of loads and stresses. The testing process was broken down to 3 stages, first, a baseline test with loads in compliance to 14 CFR 25.305 (FCC Regulation). Second, the Barely Visible Impact Damage (BVID) panel was exposed to loads to check the ultimate strength in requirement with 14 CFR 25.305 (FCC Regulation). Third, the panel was loaded, and the axial loads were increased while the failure process was monitored until catastrophic breakage point was reached. After a thorough inspection and analysis, it was concluded that panel followed all the regulations and their experiment provided reference and validation for a theoretically predicted failure and load bearing capability.

Dae-Yun Bae et al [12] proposed an active monitoring system that is alert to the defects that might develop over time, hence constantly diagnosing the fuselage, preventing the damage from reaching critical mass. Fuselage damage originates from specific hotspots in proximity to rivets and fastener holes in lab-joints. Hence, they conceived a strategy to improve and expand the detection area, rate and accuracy of monitoring system by implementing a sensor network of serial-connected PZT connected in conjunction with an Ultrasonic Propagation Imaging (UPI) system. The PZT sensors were appropriately placed to cover the optimum amount of fuselage skin and at a suitable distance from the stringer. Cracks of varying depth were made in areas where they would naturally occur. The system could create both 3-D and 2-D maps of the fuselage skin and could provide detailed location and information of all the cracks to a certain degree of error, when the UPI and the Milti-timeframe Ultrasonic Energy Mining (mUEM) system worked in tandem. The authors concluded that structural health management (SHM) system was a cheap and viable solution to detect faults in the structure of the fuselage, acting as a maintenance system.

R. Sunder et al [13] identified the general lack of consensus in analytical studies on fatigue crack growth when exposed to biaxial loading caused by cabin pressure in the fuselage. This inability or lack thereof reproducible and digitally controlled system to test this phenomenon persuaded them to construct a standardized experimental setup and investigate for the circumferential crack progression in fuselages of aircrafts. The experimental setup devised by the authors is given in figure 2. The main goal was to practically validate the theoretically predicted stress intensity range under biaxial forces and the FEM based model, hence confirming its ability to estimate crack sizes. Second, using Marker-TWIST, a modified version of TWIST load spectrum generated qualitative fractography. After conducting the tests on steel and AL-alloy, the results were analysed, and they concluded that the crack growth was intrinsically connected to the biaxial load and spectrum loading.

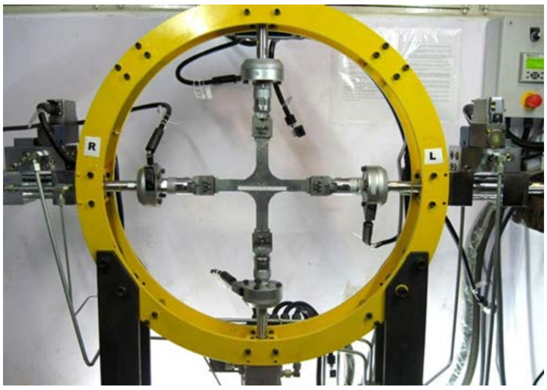

Figure 2. Experimental load frame setup for the application of biaxial forces on a fuselage cross section. [13]

Ren Yiru et al [14] analysed the crashworthiness of the fuselage that had been modified to accommodate a sine wave beam instead of the traditional fuselage bottom. The modified fuselage and the conventional one were dropped from a height. The energy dissipation along with acceleration and velocity of the fuselage and its displacement (compression) was noted. The sine wave beamed fuselage reduced the initial peak load and also increased energy absorption of the structure and unlike the conventional fuselage, the cargo floor didn't collide with the cabin floor, thereby avoiding a peak in acceleration at that point. The deformation of the strut decreased with an increase in its rigidity. The sine wave beam was a more effective solution than the conventional one.

Roy GEBBINK et al [15] in collaboration with the Chinese Aeronautical Establishment (CAE) devised a wind tunnel experiment to monitor the aerodynamic stability and performance in the cruising stage for different configurations of the aircraft. In tandem with this, they intended to develop a dataset for the validation of computational fluid dynamics algorithms. The setup consisted of 3 major steps, and the primary setup consisted of aerodynamics validation model (AVM) being mounted upside up on the Z-string instrument. This was followed by the AVM being mounted upside down on the dorsal blade sting. Finally, the AVM was mounted on the dorsal blade sting with a dummy Z-support installed. After an inspection of the results, the authors concluded that they had successfully established a dataset for two aircraft configurations across a wide variety of loads and flow conditions between Mach numbers of 0.4 to 0.9. They also determined that the repeatability and replication of the experimental setup and its results fell within acceptable error margins, and hence be used as the basis for future validation of experiments.

Most run of the mill commercial aircrafts with a vertical tail displayed high levels of instability at medium to high angles of attack. J. Wen et al [16] construct and put an aircraft to the test to encapsulate the specific structures of the aircraft contributing to the yawing moment. In order to individually test parts and check its effect on the whole aircraft, they decide to have all the parts be detachable. They investigated this characteristic using particle image velocimetry (PIV) in tandem with a pressure test. The results indicated that vertical tail and the fuselage were mainly responsible for the yawing motion of the basic aircraft. They concluded that flow field in major regions of the fuselage were adversely affected by increase in the angle of attack which was heavily responsible for the instability.

ZurriatiMohd Ali et al [17] developed an experiment to investigate the impact of canard angle on the aerodynamics of a blended wing body aircraft. The visualization of the air flow was enabled by using a physical mini bust model of a BWB aircraft when set at different angles of attack. A one sixth scale model with a rectangular canard was manufactured from aluminum. The tests were run at a velocity of 35m/s. The results of the tests indicated a drastic drop off in the lift to drag ratio when the angle of canard hit 15 degrees. They concluded that aerodynamic stability was drastically impacted by an increasing canard angle.

CrispijnHuijts et al [18] aims at optimizing control allocation to reduce trim drag on Blended Wing Body (BWB) aircraft. The trim drag of BWB is higher than that of a conventional aircraft, due to the increase in control surfaces. A model of the BWB was subjected to air forces in a wind tunnel at a Mach number of 0.24 in the configuration defined by the control allocation. The control surfaces of the vehicle were manually deflected to test these configurations. The control allocation optimizer uses 3 algorithms (Daisy Chain

(DC), Direct Allocation (DA) and Fixed-point iteration (FXP)) to reduce the trim drag. The trim drag was the highest with the use of DC algorithm and lowest with the use of DA. The introduced paradigm to reduce trim drag can be used for BWBs of various structures and designs.

4. Numerical Analysis of Aircraft Fuselage

Maher Bouazizi et al [19] devised an experiment to inspect the performance of hexagonal reinforced grid configuration, definitively determining the relative merits with respect to the standard orthogonal reinforced grid layout characterized by designated parameters. The objectives were, first, to investigate the changes in the functioning of fuselage with changes in design of the orientation. Second, to observe the changes when the frames were replaced with material used to strengthen the pre-existing hexagonal grid structure. The standard experiment was simulated, where the three structures were exposed to cabin pressures in varying degrees. The results were examined on basis of Eigen frequencies, stress experienced by the fuselage and displacement in the structure of the fuselage by keeping length of each stringer the same and the configuration in terms of number of grids in the axial and longitudinal direction the same. The design of the fuselage panels is given in Fig 3. The results showed that the Hexagonal Grid Stiffened Panel (HGSP) with frames fared the same with respect to Orthogonal Grid Stiffened Panels (OGSP) but was considerably lighter. But the strengthened HGSP without frames showed higher Eigen frequencies and lower radial displacement responses with increased stresses in the in-plane shear stress in the skin. This clearly indicates that there is an optimum condition to be reached in terms of frames with hexagonal grid pattern.

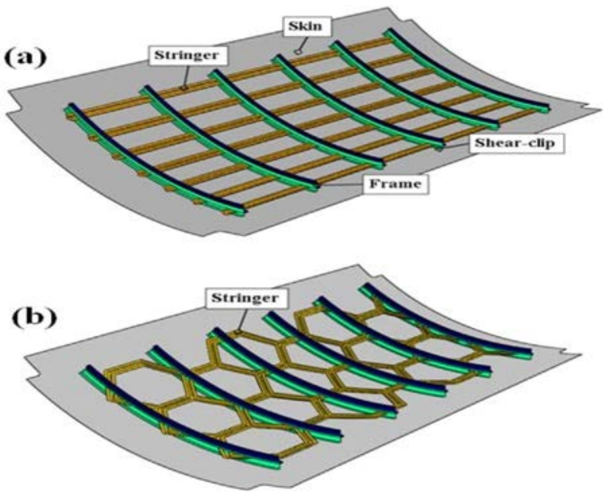

Figure 3. (a) Orthogonal Grid Stiffened Panel with Frames (b) Hexagonal Grid Stiffened Panel withFrames. [19]

P.Linde et al [20] recognized the increasing role stiffened fuselage panels with laminated construction played on the aircraft and found the need to test the post bucking behaviour of these panels under load. ANSYS and LS-DYNA were the software packages used for modelling and testing the finite element. Delamination and boundary conditions were explicitly considered during modelling. Mathematical computation of the panel through and after the buckling was discussed and a connection was established between them. It was also noticed that the modelling of the boundary condition influenced the structure. Though no sample set of data was explicitly presented, the research claimed that the numerical model was in accordance with the experimental results.

D.Perfetto et al [21] aimed at validating a new numerical model of a fuselage drop test by comparing it with experimental results. A physical and numerical drop test of fuselages containing dummies was conducted and then compared. The components of the fuselage were first accurately modeled. Then the simulated aircraft was made to land with a pitch of 2.28 degrees, replicating the fall of the actual physical model. The deviations between the mathematical and experimental deformations were within the range of 90mm. The numerical model was not as rigorously drafted as it should have been, therefore, it was prone to errors. Nonetheless it was an accurate system.

F.Marulo et al [22] recognized the growing versatility of new age composite materials and intended to configure ways to integrate them into the aircraft fuselage, which is in line with regulations. The main objective of their research was to envisage new designs for the lower lobe of the aircraft fuselage primarily comprising of materials. They also intended to codify concrete procedures to test and incorporate these materials into future designs whose features aids in its response to crashes or “crashworthiness”. Qualities like energy absorption and crash response were put to the test with a combination of simulators like LS-DYNA and FEM models, recreating the test on a real fuselage. These tests were first performed on the barrel section of the fuselage and then specifically to the detailed lower lobe of the fuselage, giving attention to how each individual part performed in the event of a crash. They concluded from the results that pre-existing structures mainly stanchions in current day airplanes, need to be redesigned to enhance the effectiveness of composite materials in fuselage designs.

MOU Haolei et al [23] inspects the crashworthiness of fuselage section made up of composite skins. Drop test for each of the structure was simulated on the LS-DYNA software with an impact velocity of 6.67m/s. Three rows of seats with concentrated masses on them were modeled (using Hyper Mesh), but only the central row was considered. The acceleration response and failure mode of the fuselage were noted for structures with skins of different ply number and ply angle. An increase in ply number increased fuselage stability, but also caused a rise in stress and led to earlier peak acceleration. With certain values of ply angles the energy absorption by the fuselage structure became more efficient, also decreasing stress values. The aforementioned results validated certain composites, thereby affirming the fact that ply number and ply angle play an important role in improving the crashworthiness of a structure.

YuchenWena et al [24] conceived an experimental setup to check the feasibility and the extent to which minute errors in a composite fuselage formed during the manufacturing process, can be fixed using a set of actuators without critically damaging its structural integrity. A FEM of a composite fuselage with appropriate parameters along with fuselage geometry, fixture structure and actuators design and positioning was constructed. This model is further refined based on data collected from results of the same setup executed in real life so as to accurately mimic the fabrication process. This is followed by failure test, stress/strain analysis and a dimensional control analysis. The results showed that the actuators were capable of modifying the fuselage to the ideal shape with less than 1000 pounds of force without causing damage to the composite fuselage. In general, they concluded that their procedure could be used to make corrections to deformed fuselage and requires more research to make the process more efficient.

Ju et al [25] analyzed the dynamic Stress Intensity Factor (SIF) of a longitudinal crack in the fuselage when subjected to various types of loadings. The FEM generated was subjected to both triangular and trapezoidal loads (dynamic loads) along with various static loads for various crack sizes with varied time intervals of application and there after their respective graphs were compared. The peak SIF value obtained under dynamic loading was greater than that seen under static loading and this variation increased with increase in crack size. The dynamic SIF curve and the dynamic load curve applied, share similar shapes. The dynamic SIF curve sees considerable changes when the loading time varies. The stimulated data obtained was in accordance with the theoretically predicted observations.

Venkatesha B K et al [26] probes the rate of growth of a longitudinal crack due to fatigue. The frames ability to arrest the growth of a longitudinal crack was tested. MSC NASTRAN was used for stress analysis of the modeled panel. The load and the boundary conditions were applied such that the tensile load due to internal pressurisation was uniformly distributed through the cross-section. A crack was initiated at a rivet hole which happens to be the location of the maximum tensile stress. Modified Virtual Crack Closure Integral (MVCCI) determined the SIF and the damage growth rate under constant fatigue loading were obtained. SIF increased with increase in crack length, but its value decreased on nearing a frame. Fatigue crack growth rate increased with loading cycles and as these cycles increased, the growth rate shot up till it reduced when the crack reached the frame.

Chuin-Shan Chen [27] aims to predict the residual strength of a fuselage under the crack tip opening angle criterion. A study on ductile tearing simulation was also presented, with an analysis on thin shell finite element. A fuselage panel with a saw cut, was subjected to pressure until a crack stretching across two frame bays was developed. A finite element model of the panel was generated to assess the crack growth. The Crack-Tip Opening Angle (CTOA) from flat panel tests was calibrated and then the theoretical data was compared with the experimental one. Results showed that a panel with multiple site damages had a residual strength reduced by 28 to 47%. The residual strength also changed with change in CTOA. A broken tear strap caused further reduction in strength by 24 to 30%.

Mario Jaime Martin-Burgos et al [28] recognizes the inadequacies in present day simulation softwares to adapt the computational grid upon encountering deformation or irregularities in the surface being computed for, requiring them to reconstruct the mesh at every step. These shortcomings in the simulations normally cluster around interstices of components with varying topologies like fuselage-wings or intersections of moving parts. The authors hence construct an algorithm which enables the simulations to adapt the model to an acceptable degree of error structured around preexisting CAD geometry. They begin by explaining the mathematical construct of Non-Uniform Rational B-Spline (NURBS) which enables the algorithm to make alterations based on the degree of change. Finally, this strategy is tested under scenarios where there is a variation in the form of the deformation, mainly an irregularity in the surface, angular and lateral displacement of the component of the wing with respect to the fuselage and were cross verified with preexisting data of the aircraft DLR-F6. Upon examining the results, they concluded that this strategy is most efficient when restricted to only 2 NURBS panels and any more would lead to a skewed representation of the structural geometry of the components.

Lucjan et al [29] overlooks the failure in the wing fuselage connector due to the periodic loads acting during flight in the presence of metallic corrosion. A visual inspection of the broken connector revealed the site of the origin of the crack. A finite element model of the connector developed on the Patran 2000r2 program was subjected to stresses. The crack development was observed under 2 analysis methods which subjected the aircraft to loads during take-off, flight and landing. The analysis method revealed that the aircraft had an average flight time of 4000 to 5000 hours, before succumbing to pressure and finally cracking. It was also found that an excessive loading of the aircraft by a mere 10% reduced its flying hours by a considerable 40%. Corrosion was found to accelerate the crack growth. Having a fuselage wing connector with better load carrying capacity is thereby recommended.

The T-tail, a crucial member of the empennage, provides stability to the aircraft. At certain speeds above the flutter speeds, leads to abrupt and large oscillations and ultimately catastrophic failure of the empennage. The research conducted by QiuJu et al [3] aims to characterize the variation in flutter patterns with modifications in the support stiffness provided by the rear fuselage. The main objective of the paper was to establish detailed designs of the rear fuselage which were modeled using Circumferentially Uniform Stiffness (CUS) or the Circumferentially Asymmetric Stiffness (CAS) configurations as a template, using optimization technique in tandem with Multi-Island Genetic Algorithm (MIGA). The FEMs of the T-tail and rear fuselages were developed and were implemented into the optimization loop. The optimization loop essentially set design variables and constraints. The results of the optimization loop tests pointed to a slight advantage of the CAS composite over the CAS configuration due to its relative lightness and aeroelastic tailoring. They also deduced that with increase in twisting and bending, there is an increase in flutter speeds. And flutter speeds of less than 200 m/s essentially provide no advantages in stability and are unwelcome.

5. Summary of Literature Review

The Relentless pursuit of improvements in performance has seen ceaseless growth in the aircraft industry. This has inevitably led to the proliferation air travel to the masses and ensuring a safe and comfortable flight has called for rapid innovation in the field of design and development. ASAC attenuates any sound generated due to the fuselage inside the cabin, if shaped elliptically endures larger stresses than its circular counterpart, making the fuselage highly reliable. Airworthiness saw a rapid increase when a new aircraft assemblage system relying on GPS replaced the old mechanical one. To make the flight more economical for the daily user, neural networks can be used to generate an optimal structure for reduced drag and greater lift. Flutter reduction by span length variation and the adding of Trailing Edge Devices for greater aerodynamic efficiency promises the passenger a comfortable and steady ride. In case of storms or erratic weathers the incorporation of Navier Stokes equations during design would prove beneficial.

The genesis of every successful aircraft design can be drawn back to incremental gains made in the wind tunnel. The wind tunnel is more crucial than ever before in modern era of aviation, in spite of the emergence of simulation techniques involving CFD. Vortex generation and its convolution in the presence of perturbations at different angles of attacks involving different structures (chimed, blended wing body, slender body etc.) is diligently investigated in the wind tunnel. Another method of validation has been the subjugation of critical fuselage sections to extreme mishaps. A series of sensors placed make tangible the physical forces acting and deforming that particular section. Aircraft controllability is finally checked with the actual flight, legitimising the data obtained from the wind tunnels.

A cost-effective time intensive validation method has been used and developed since the late 50’s where in the aircraft modelled (FEM) is rigorously worked upon by equations (CFD) simulating an in-flight experience. The simulations can be further refined by incorporating Neural Networks and Back Propagation Algorithms in the design process, keeping the results more faithful to experimental results. The data collected is primarily validated by experimental verification, after which, the simulation becomes a new paradigm for further testing. Crashworthiness of sections can be carried out multiple times without incurring any experimental costs with the added convenience of varying the parameters for every iteration. Constant monitoring of fuselage through the datasets from sensors across the fuselage surface enables us to highlight and predict regions most susceptible to failure and by virtue generate cracks, acting as a health management system. Stability and behaviour of various aircrafts under the influence of vortices and complex air currents can now be easily probed into without the actual construct of a wind tunnel. Self-optimisation algorithms also facilitate computational modifications to the aircrafts allowing for the development of the most aerodynamically efficient system.

6. Conclusions

The incremental advances made in the aviation department might seem miniscule individually, but in the grand scheme of things, have had a revolutionary effect in aircraft fuselage design. New age composite materials hold great promise in weight shedding of the fuselage, but problems in the manufacturing process acts a roadblock towards incorporating them into aircraft body. Great strides were made to standardise the manufacturing process and tackle these challenges. The rise of analytical softwares in tandem with computational analysis has ensured that most efficient fuselage models are constructed with a relatively small impact financially. Attempts to implement preemptive warning systems which reduce the risk of failure and give a more holistic idea about the functioning of the plane are making great strides and are on the verge of mass implementation. In this race to optimise and improve the efficiency of the manufacturing, the comfort of the passengers has not been forgotten. Active management systems to attenuate the disturbances throughout the fuselage structure are one of many techniques implemented to increase the comfort of the ride

Fuselage technologies are currently experiencing an interim period where only incremental advances are being made without major design changes. Aircraft still religiously stick to the metal semi-monocoque design as the fundamental structure of the fuselage. Radical ideas like the blended wing concept are currently still in the design process in the commercial context. Fuselage concepts which majorly alter their structuring to better suit performance and aerodynamic efficiency are the future of the aircraft. Further studies are being conducted on self-healing composite materials and ways to incorporate nanotechnology are currently being devised.

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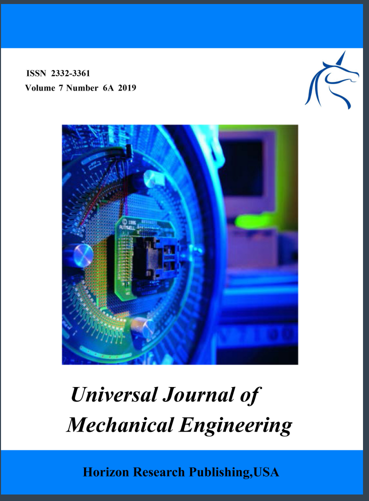

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