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Highlights

Transonic Wind Tunnel

Principle of Quasi Work

Typical Aerospace Applications

Advanced Composite Materials

Discovering Thoughts, Inventing Future

VOLUME 14 ISSUE 1 VERSION 1.0

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Design and Analysis of Transonic Wind Tunnel

By T. Kumaraswamy, V. V. S. Nikhil Bharadwaj & Parthasarathy Garre

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Abstract- The Transonic Wind Tunnel is used to test aircraft models at speeds from Mach number 0.2 to 1.4. Transonic flows consist of mixed subsonic and supersonic flow regions. Shocks can occur in these flows but often do not have a strong enough pressure gradient to assume flow properties similar to those of supersonic flows. These regions are difficult to model mathematically because they have characteristics of subsonic and supersonic flows. In this regard, the paper is aiming towards the design and analysis of the transonic wind tunnel performance by considering two phases namely automated design and its evaluation. Modern optimization software is combined with isentropic relations; simulations are analyzed to design a Mach 1.2 nozzle with maximum test length. The optimal design has an unconventional shape described as compound curvature, which makes the contour appear slightly wavy in AutoCAD. The same is evaluated and found satisfactory for the proposed modification of the test section in the wind tunnel in fluent analysis.

Keywords: transonic, mach number, AutoCad, fluent, hypermesh, analysis.

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Design and Analysis of Transonic Wind Tunnel

T. Kumaraswamy [α], V. V. S. Nikhil Bharadwaj [σ] & Parthasarathy Garre [ρ]

Abstract- The Transonic Wind Tunnel is used to test aircraft models at speeds from Mach number 0.2 to 1.4. Transonic flows consist of mixed subsonic and supersonic flow regions. Shocks can occur in these flows but often do not have a strong enough pressure gradient to assume flow properties similar to those of supersonic flows. These regions are difficult to model mathematically because they have characteristics of subsonic and supersonic flows. In this regard, the paper is aiming towards the design and analysis of the transonic wind tunnel performance by considering two phases namely automated design and its evaluation. Modern optimization software is combined with isentropic relations; simulations are analyzed to design a Mach 1.2 nozzle with maximum test length. The optimal design has an unconventional shape described as compound curvature, which makes the contour appear slightly wavy in AutoCAD. The same is evaluated and found satisfactory for the proposed modification of the test section in the wind tunnel in fluent analysis.

Keywords: transonic, mach number, AutoCad, fluent, hypermesh, analysis.

I. Introduction

Test facilities such as wind tunnels require stringent control of test parameters such as wind speed, temperature, pressure, etc., in order to satisfy the objectives of the simulation [1]. Gases consist of molecules moving in random motion with negligible cohesive forces. Depending on the speed of the gas, it can be approximated as either an incompressible or compressible substance. An incompressible substance is one that does not experience significant density changes throughout the substance, or the medium. This situation can be found in low speed flows, where the kinetic energy is negligible to the thermal energy found in the medium. Higher speed flows, where the kinetic energy is comparable in magnitude to the thermal energy, will have varying densities throughout the medium and are thus considered compressible substances [2]. When a body is placed in a gas flow, disturbances will form and propagate through the medium. A given disturbance will affect those molecules closest to the body and will collide with the surrounding molecules. In incompressible flows, the distance between the molecules will be maintained through propagation of the disturbance, but in compressible flows, the molecules will contract closer to each other before returning to their original distance after the disturbance [3]. The speed at which a disturbance propagates through a medium is the speed of sound. The non-dimensional number that expresses free-stream velocity with respect to the speed of sound of a medium is the Mach number (*M*). Flow properties can be established by the value of the Mach number. Flows that have a low Mach number, $M < 0.3$, can be assumed incompressible flow, while anything above this is considered compressible flow. The compressible flow regime can be further broken down into subsonic flow, $M < 1$, transonic flow, $0.7 < M < 1.2$, and supersonic flow, $M > 1$ [4]. Transonic flow is a special case of subsonic flow. The transonic flow field is characterized by regions of mixed flow where there may have been a shock incident on a surface yielding supersonic flow upstream but subsonic flow immediately behind it. In most situations, shocks can be considered negligibly thin compared to any other length scale in the flow (thicknesses on the order of 10^{-5} cm are typical). In addition, despite the fact that the Mach number lies between 0.8 and 1, the analytical solution of the conservation equations is much more difficult since neither the elliptic equations used to solve problems in the subsonic regime nor the hyperbolic equations that govern the supersonic flow regime are strictly applicable for the transonic flow regime. There are many parameters that characterize the TWT such as test section dimensions, operating characteristics (Reynolds number, Mach number), general capabilities of the facility (Mach number range and maximum Stagnation pressure) [5]. A maximum Mach number of 1.8 is possible in the transonic test section [6].

II. Dessign of Transonic Wind Tunnel

Computations generally begin at the throat using a transonic scheme to compute the flow near the throat, assuming the flow is nearly parallel there. Thus, the upstream subsonic flow must deliver a nearly parallel flow to the throat. These transonic schemes are only valid for Mach numbers very near one and require some input regarding the shape of the nozzle near the throat, such as the throat radius of curvature. Full-scale aircraft or vehicles are sometimes tested in large wind tunnels, but these facilities are expensive to operate and some of their functions have been taken over by

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computer modeling and analysis in our case. Testing at transonic speeds presents additional problems, mainly due to the reflection of the shock waves from the walls of the test section. Therefore, perforated or slotted walls are required to reduce shock reflection from the walls. Since important viscous or inviscid interactions occur (such as shock waves or boundary layer interaction) both Mach and Reynolds number are important and must be properly simulated by selecting optimum design of nozzle and then analyzed in CFD.

The wind tunnel consists of five basic parts. The first part of the design was the contraction nozzle section that takes the high pressure low speed air from the settling chamber and converts it to low pressure high speed flow. The second part that was designed was the test section where the object being analyzed will be placed and tested. The choke block was the third part in the design. The choke block set the Mach number in the test section by changing the area ratio at the end of the test section. The diffuser was the forth designed part, and it reduces the flow speed and routes it out of the facility. The last part of the wind tunnel design was the stand. The stand allows for easy alignment in the settling chamber and for easy movement of the wind tunnel to storage when it is not in use. The AutoCAD software was used to model all of the components for the wind tunnel. An AutoCAD drawing of the full transonic wind tunnel design except for the diffuser support is shown in figure 1.

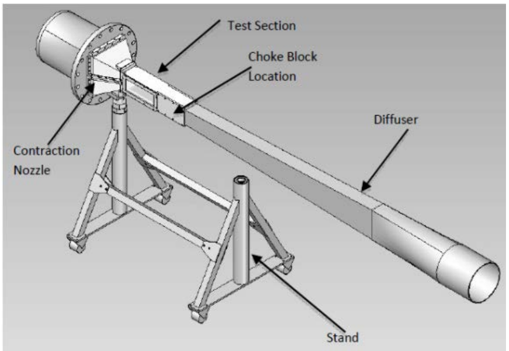

Figure 1 : CAD drawing of wind tunnel

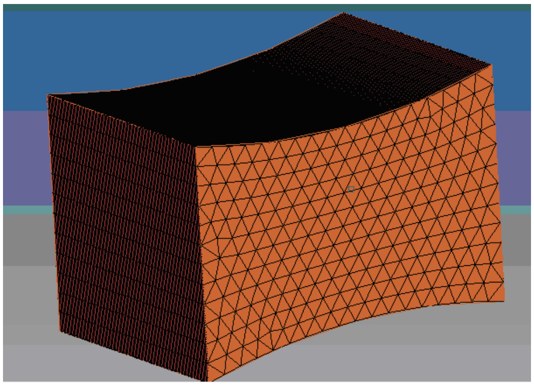

Figure 2 : Tetra mesh of wind tunnel

The meshing for analysis was done in Hypermesh as shown in figure 2. Blow down tunnels use the difference between a pressurized tank and the atmosphere to attain transonic speeds at the Test Section of the wind tunnel so that models of interest can be tested at transonic conditions for a short duration of time. The Sizing of Blow down wind Tunnel of 4 X 4 ft test section for varying M= 0.8 to 1.2 is considered here. The key driving design factors for wind tunnel can be the wind tunnel must be able to produce uniform transonic flow at the design Mach number in the test section, it must have the flexibility of being able to operate within a range of specified mach numbers, the run time must also be sufficient for testing purposes and theoretical run time calculations were performed in order to decide on the test section size. The basic fluid mechanics assumptions made for the flow in the wind tunnel includes fluid is air, flow is isentropic in the tunnel, ideal gas and air in the tanks undergoes polytrophic expansion.

High pressure air storage system will be dependent on the mass flows required and the frequency of runs. Pressure storage tanks are available on the shelf bases which are mounted horizontally or vertically. Tanks are painted black to absorb heat. They are provided with safety disk or pressure relief valve. As air is drawn from the storage, polytropic expansion takes place within the tank. This results in drop of reservoir temperature which is very bothersome. Fall of stagnation temperature causes resultant change in the stream temperature for a given Mach number. Change in temperature results in the change of viscosity which in turn affects the boundary layer thickness. Changes in Reynolds number and Mach number during a run are thus consequential to the fall in reservoir temperature. To maintain constancy of stagnation temperature, it is a practice to stack the reservoir volume with empty metallic cans. They serve as heat storing matrix during compression and release heat during the expansion process. Another way to maintain the constant stagnation temperature is by providing heater units in the reservoir.

The test section is situated downstream of the Nozzle. The dimensions of the test section were given to be 120cm X 120cm cross sectional area. The length of the test section was taken to be 180 cm. The temperature and velocity turbulence level of the flow in the test section region is low provided the velocity in the settling chambers is low and the contraction ratio going from the settling chamber to the minimum section of the nozzle is kept large (on the order of 24cm). From the point of view of the pressure loss calculation, the test chamber will be considered as a constant section duct with standard finishing surfaces. Apart from temperature ratios, pressure ratios, cross-Sectional area ratios, some other parameters are dynamic pressure, mass flow rate, test section velocity, maximum velocity and free stream Reynolds number.

Design of transonic nozzle is passage used to transform pressure energy into kinetic energy and delivering flow at transonic speeds. It needs a combination of convergent and divergent nozzle (CD Nozzles). To deliver a transonic flow at the desired Mach number, the flow should be wave free and parallel. An improper contour results in the formation of finite shocks inside the nozzle by coalescence of weak waves and can prevent a uniform flow. The Method of Characteristics (MOC) provides a technique for properly designing the contour of the transonic nozzle. A method of characteristics is a very elaborate procedure for the creation of an accurate set of data points to create a nozzle, be it for a sharp expansion nozzle or a wind tunnel nozzle with a radius placed at the throat for more uniform flow at the exit plane. A transonic wind tunnel uses this method to create an expansion nozzle similar to those found on axisymmetric rocket engines to expand air to transonic speeds at the test section. The flow accelerates through a converging duct ($M < 1$) and arrives at the throat (A_t) beyond which the geometry for smooth expansion is derived from the Method of Characteristics.

A diffuser is a device that is used to convert kinetic energy into enthalpy, pressure energy for an incompressible flow. For subsonic or transonic operation diffuser area increases and for supersonic flow, diffuser area decreases. In supersonic or transonic wind tunnels, most commonly used diffuser is of convergent divergent type (also called the second throat diffuser).

The supersonic or transonic nozzle is fitted behind the settling chamber. The settling chamber, to which a pressure gauge is attached, is used to maintain the stagnation pressure to provide flow to the nozzle. Settling chamber is made to with-stand a pressure about 10 atmospheres. It is made of mild steel usually.

Screens are used in settling chambers to gain the uniformity in the flow by reducing the turbulences. The screens are subjected to large stresses because of the large stagnation pressures used in the tests and because of the possibility of pressure shocks during the initial and final phases of the runs. In order to decrease the stresses, the screens may be placed in such a way that they present curved surfaces to the stream. Often supporting screens of large mesh and large diameter wires are placed behind each screen of fine mesh.

III. Analysis in Fluent

Fluent is a state of the art computer program for modeling fluid flow and heat transfer in complex geometries fluent provides complete mesh flexibility, including the ability to solve your flow problems using unstructured meshes that can be generated about complex geometries with relative ease supported mesh types includes 2D triangular-quadrilateral, 3D tetrahedral, hexahedral, pyramid, wedge, polyhedral and mixed meshes fluent also allows to refine your grid based on the flow solution. Fluent is written in the C computer language and makes full use of the flexibility and the power offered by the language. Consequently, true dynamic memory allocation, efficient data structures and flexible solver control all are possible. Initial conditions used are the specific heat ratio as 1.4, the stagnation temperature as 300K, the initial air supply tank temperature as 300K, the initial tank pressure as 11 bar, final pressure as 7.5 bar, stagnation pressure as 2 bar, the air supply tank volume as $18931 m^3$ and n as 0.768 for air as the polytropic exponent of expansion with 10 number of tanks. The wall boundary conditions are as shown in figure 3. Analysis results of the pressure coefficients contours are shown in figure 4.

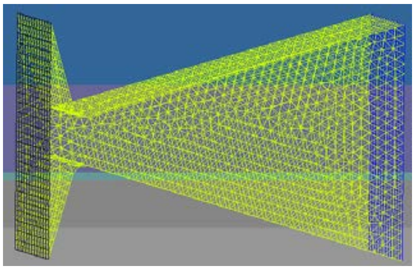

Figure 3 : wall boundary conditions

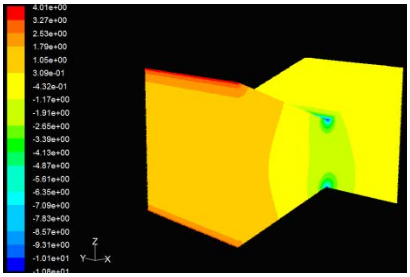

Figure 4 : contours of pressure coefficients

IV. Conclusion

The sizing of the new transonic wind tunnel is done. The results of CFD fluent keeping Area ratio constant with change in velocity, static pressure and pressure coefficient were found satisfactory. A response surface is constructed from a user-specified set of contour shapes for optima which is defined as the shortest nozzle with the maximum test length. This is achieved by delaying transition along the nozzle wall. The new design incorporates a section of increased diameter with the intention of enabling the tunnel to start in the presence of larger blunt models. The resulting flow fields are analyzed to see the shock effects and shear layers have on the test section flow and are good for nozzle design of Mach 1.2.

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Advanced Composite Materials in Typical Aerospace Applications

By Sanjay Kumar Sardiwal, Md. Abdul Sami, B. V. Sai Anoop, Gudipudi Susmita, Lahari Vooturi & Syed Arshad Uddin

MLR Institute of Technology, India

Abstract- Composites are becoming increasingly important in the aerospace industry. At least 30-40 per cent of modern airframes are now made of composites, and this percentage is increasing rapidly due to technological advances in the field. The use of composites for primary structures such as fuselages and wings has grown significantly in transport aircraft. Apart from increased strength at lower weights, composites also meet fatigue and damage tolerance, gust alleviation, and low noise foot print requirements. This paper examines the challenges and advantages of using composites in airframe manufacture, as opposed to other alloys. It also looks at the ways and means to ensure that safety and durability are not compromised by the use of composites. The prime objective of this paper is to highlight the use of advanced composite materials in the field of aerospace and to encourage readers to understand and to write papers on such topics.

Keywords: composites, polymers, matrices, resins, sandwich structures.

GJRE-D Classification : FOR Code: 861301, 090102

Advanced Composite Materials in Typical Aerospace Applications

Sanjay Kumar Sardiwal [α], Md. Abdul Sami [σ], B. V. Sai Anoop [ρ], Gudipudi Susmita [Ѡ], Lahari Vooturi [¥] & Syed Arshad Uddin [§]

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Keywords: composites, polymers, matrices, resins, sandwich structures.

I. Introduction

The need for the highly effective and efficient material which should be concerned with the ecology – concerned world of finite resources has led advanced composites to be one of most important materials in the high technology revolution in the world today. As we all know if the demand increases, the availability should also be increasing. The increased availability of these light, stiff and strong materials has made it possible to achieve a number of milestones in Aerospace technology. Metallurgists and designers have advantageously used these materials in the construction of modern fuel efficient aircraft, satellites, missiles, launchers and other space vehicles.

a) What are composites?

They are a blend of two or more materials and/or technologies brought together to produce an item giving specific characteristics for a particular application. The term composite is often used both in the modern context of Fibre Reinforced Plastics (FRP) and also in the wider context to cover honeycomb structures and bonded metal laminates for primary structural applications. The fibers or matrix (resin) alone cannot be used for any applications limitations in other properties. Fibers are thin and integrity is not maintained. Fibers are comparatively heavier. In matrix materials the modulus and strength values are less and hence matrix alone cannot be used for any structural applications. but when these two materials are combined we get a composite materials which is light weight, stiff, strong and tough.

b) Why Aerospace?

When it comes to safety and security the aerospace is one sector which needs a word "super" to be prefixed with these words "safety" and "security". Imagine a structural failure in a car and an airplane. if the skin of the car gets ripped off while driving no disaster is going to happen. What if this happens in an airplane? The picture shown below will speak to you better.

Figure 1 : Fuselage damage to Aloha Airlines Flight 243, April 1988

II. Components of Advanced Polymer Composites

Advanced polymer composites generally contain reinforcing fibres in the form of continuous filamentary tows or fabrics and properly formulated polymetric matrices. Structural adhesives (mostly in the form of supported or unsupported film) and honeycomb cores are also used for making sandwich structures and metallic laminates.

a) Fibres

Fibres are widely used as reinforcements. Amongst the fibres available, glass, aramid and carbon fibres are in extensive use, although boron or other exotic fibres are also used in modest quantities for applications requiring very high service temperatures like the ones which we need for the skinning of the aircrafts. The properties of glass, aramid and carbon fibres are given in tables 1 to 5.

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Table 1 : Typical Properties of Glass Fibres

Properties	'E' glass	'R' glass	'D' glass
Density g/cc	2.60	2.55	2.16
Tensile strength, MPa	3400	4400	2500
Tensile modulus, GPa	73	86	55
Elongation at break, %	4.5	5.2	4.5
Filament diameter, μ	3-14	3-24	3-14

Table 2 : Typical Properties of Aramid Fibres (1)

Properties	Kevlar 49	Kevlar 149
Density g/cc	1.38	1.41
Tensile strength, MPa	3620	3447
Tensile modulus, GPa	127	175
Elongation at break, %	1.85	2.9

Table 3 : Properties of High Tensile Carbon Fibres (2)

Properties	T300	T400	T800	T1000
Density g/cc	1.75	1.80	1.81	1.82
Tensile strength, MPa	3528	4412	5588	7060
Tensile modulus, GPa	230	250	294	294
Elongation at break, %	1.50	1.80	1.90	2.4
Filament diameter, μ	7.0	6.8	5.2	5.3
Precursor	PAN			

Table 4 : Properties of High Modulus Carbon Fibres

Properties	M 30	M 40	M50
Density g/cc	1.7	1.81	1.91
Tensile strength, MPa	2920	2744	2450
Tensile modulus, GPa	294	392	490
Elongation at break, %	1.3	0.6	0.5
Filament diameter, μ	6.3	6.5	6.3
Precursor	PAN		

Table 5 : Properties of High Modulus High Strain Carbon Fibres

Properties	M 35J	M 40J	M 46J	M 55J
Density g/cc	1.75	1.77	1.84	1.91
Tensile strength, MPa	5000	4410	4210	2450
Tensile modulus, GPa	343	384	440	490
Elongation at break, %	1.6	1.2	1.0	0.5
Filament diameter, μ	5.2	5.2	5.1	6.3
Precursor	PAN			

It is evident that over the years substantial development has taken place in carbon fibre development work. Initially the trend was that the higher the modulli the lower the strengths (table 4). with improved precursor, method of graphitization and other parameters the production of fibres with higher strain was achieved and this has resulted in the availability of fibres with excellent mechanical properties.

b) *Matrix*

Matrices are essential ingredients to embed fibres and provide a supporting medium for them. It is the ability of the matrix to transfer stresses which determines the degree of realization of mechanical properties of fibres and final performance of the resultant composites. Stress-strain behavior and adhesion properties are important properties are important criteria which control the ability of the matrix to transfer stresses. A lot of research is being carried out on the basic understanding of the relationship between properties and production of tough, strong and stiff and environment resistant composite structures. This has helped in the development of composites having acceptable properties.

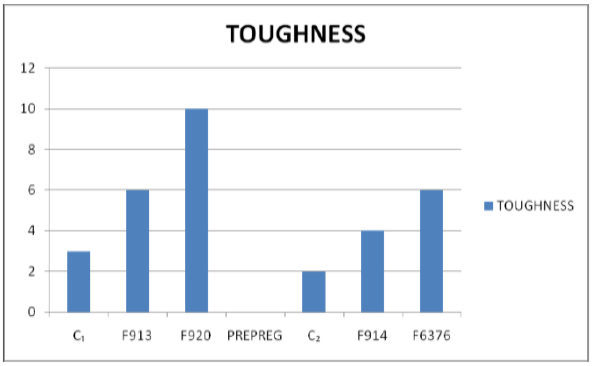
III. PROPERTIES

a) *Toughness*

In order to suit themselves for the aerospace applications it requires greater damage tolerance, high modulus, high strength and service temperatures of about 150ºC and above.

But there are these factors which affect this from happening.

In a brittle matrix full realization of mechanical properties of fibrous reinforcement are not achieved. Especially, impact properties of resultant composites are poor. Usually, the toughness achieved by flexibility of the polymer backbone or by external plasticity by using reactive dilute. By this method, although the impact strength is improved, the sacrifice of high temperature capability is inevitable. Another way of toughening matrix or adhesive systems is by inclusion of dispersed phase in the glassy matrix. Although the mechanism of toughening is not fully conclusive, it is believed to arise from stoppage or alteration of the mode of propagation of micro crack(s). Reacting with CTBN rubbers and alloying with thermoplastics thermosetting resins can be toughened. It is obvious that significant achievement has taken place in the toughening of epoxy based matrices. Composites made from these new- generation 175ºC – curing machines and recently developed high strain fibres, almost satisfying the requirement needed for a material to be used in aerospace application.



C_1: 120C curing epoxy based system not formulated for toughness

C_2: 175C curing system based on widely used MY 720 and DD

Figure 2 : comparison of toughness of carbon fiber composites based on toughened and untoughened epoxy system

b) *Heat, Humidity and Chemical Resistance*

Better maintenance of mechanical properties over a wide range of temperature is an essential for structural composites. Polymers with higher aromaticity tend to have higher T_g toughness and T_g often call for optimization. Resistance to hot and wet conditions and various solvents, and fire retardancy is also required. Composite products which are used for interior furnishing of civil aircrafts and surface vehicles need to meet stringent requirements of lower smoke generation and least toxicity under pyrolytic conditions. Phenolic resins are chosen as base matrix materials for making composites for such high heat and fire-safe applications.

c) *Ease of Handling and Processing*

Handling and processing characteristics are equally important. The resultant properties of finished composite items are dependent on how well the composite raw materials are manipulated and processed. Shelf life, tackiness and drapability are the important criteria for laying up, winding and stacking by shop floor operators. Specifications in respect of these are met by judicious selection of hardeners, modifying additives and other relevant considerations.

The technique of partial advancement of partial advancement of resin matrices is conventionally employed in the preparation of fibrous pre- impregnates which are subsequently used for fabrication of composite items by heat and pressure. The shelf life of such impregnates is limited and production of void- free cured composite items is sensitive to processing conditions with respect to heating rate, time of application and duration of pressure and cure temperature. Dynamic viscosities of two matrices with controlled flow and a widely used system based on MY 720 and DDS. A straight up simple cure cycle can be employed for Fibredux 913 (a trade mark of CIBA-GEIGY) and Fibredux 914 composites systems where as a dwelled complex cure cycle is necessary for MY 720/DDS system. It is evident that this cure cycle is difficult to monitor because one has to apply pressure when a particular viscosity is attained in order to avoid running away of resin its fluid state. A number of cure cycle can be employed for a matrix system with controlled viscosity and reactivity.

IV. BASIC POLYMERS FOR MATRICES

- *Epoxy Resins*

Epoxy resins are still the work- horse of advanced polymer composites today.

- *Phenolic Resins*

Mechanical properties are not good as that of epoxy resins. However, phenolics are employed for applications requiring better ablative properties and low smoke generation.

- *Bismaleimides*

The class of matrix materials has a higher T_g and acceptable mechanical properties including resistance to impact. A number of systems based on bismaleimide resins are accepted for commercial production. Metamid ™ 5292 A/B bismaleimeide system has a T_g of 270ºC and attractive mechanical properties. This system is based on 4, 4′

Bismaleimidodiphenylmethane and 0, 0′ Diallyl Bisphenol A.

a) Themoplastics

Engineering thermoplastics are undergoing extensive evaluation for their use as matrices. They have good mechanical and thermal properties. Because of their excellent fracture resistance thermoplastics are superior to thermosets with respect to the damage tolerance as reflected in residual compression strengths. Residual compression strengths after impact loading of PEEK and a few thermosets as matrices are compared in the figure 4. Other advantages are long storage life short moulding cycle and reprocessibility. Inspite of the above, lack of long term performance data is one of retarding factors for their extensive use on a commercial scale. Some of the important thermoplastics are Polyether ketones, polysulphides, polysulphones, and polyamides. And some of the suppliers are ICI, Dupont, Phillips, Amoco, Ciba-Geigy, rogers, NASA, General Electric.

b) Prepregs

Pre assembled and impregnated fibres and fabrics are known as prepregs. Thus are preferred by users in the aerospace industry as they have the following advantages:

i. They are supplied in ready to use form. This eliminates handling of solvents, hardeners, additives, heat resin and other chemicals
ii. Most proprietary prepegs are based on the state of the art matrix systems which are developed through extensive R&D efforts and offer the best properties with respect to toughness, environmental resistance and ease of processing to shop floor operators. These matrix systems are not available as commodity resins.
iii. Sophisticated equipment is needed for the production of quality prepegs with stringent specifications of resin and fibre weight tolerance and hence capital investment is high. this can be justified if a large volume is produced and supplied to many users.
iv. Handling of fine fibre tows for making continuous unidirectional prepegs needs skill and experience of the highest order, otherwise the reject rate could be high.

Several techniques are available for making prepegs. For high quality unidirectional (UD) prepegs, matrix film transfer and hot-melt impregnation process is adopted.

c) Surface treatment of carbon fibre

Bonds between matrices and carbon fibre, especially of high modulus carbon fibre, tend to be poor and not adequate for most applications. This has necessitated treatment of carbon fibre filaments to enhance interlaminar shear strength (ILSS) of cured composites. The treatment is based on oxidizing chemical agents. The treated fibres are given a polymeric coating before they are sent for prepegging.

V. Recent Development in Matrices

With the commercial production of high strain carbon fibres need for newer generation of polymeric matrices, having higher extensibility and greater fracture toughness, but without sacrificing high temeperature capability has become imperative. As a result, R & D oriented manufacturers of prepegs have undertaken the task of developing matrices with the following requirements:

- Good translation of properties with new high strain carbon fibres
- Improved fracture toughness and impact performance
- Straight – up cure cycle.
- Good hot wet properties upto 150º and beyond.
- Controlled flow and reactivity built in matrices for ease of processing including preassembly before curing.

To meet the above requirements a number of matrices have been developed. Other proprietary product with similar characteristics may be available. Composite properties of these matrices are given in the table drawn below.

Matrix and fibre	0º LAMINATE PROPERTIES			
	Tensile strength	Tensile modulus	ILSS,MPa	G*IC* (Toughness) JM-2
F914 + T300	1650	135	118	350
F6376 + 1M6	2696	172	131	
F 924 + T 800	2610	169	130	666
Vx M18 + M 40JB	2370	221	84	
Vx M18 + M 55J	1850	320	65	

a) Sandwich Structures

Sandwich structures, consisting of profiled or rectangular honeycomb or structural foam cores, bonded on either side to skins of metallic sheets or FRP laminates, are used in applications where extremes of lightness and stiffness are predominant requirements.

The last sentenced could otherwise be used to describe "AEROSPACE APPLICATIONS".

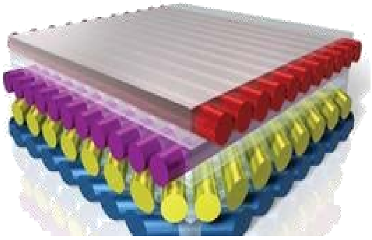


Figure 3 : A graphic indicating how the layers are arranged

The above picture otherwise depicts the way in which the different layers are arranged in the form of a pile.

b) *Processing*

A number of methods are available for processing advanced composites. Some of them are compression moulding, wet and dry winding, Resin Transfer Moulding (RTM) pultrution and bag moulding (pressure bag, vacuum bag and autoclave). In aerospace industry autoclave processing is used preferentially. For making flat sandwich panels press moulding is the most efficient and economical method which is widely adopted. Filament winding is used for making cylindrical and spherical structures. For mass production, RTM and pulstrution techniques are employed.

c) *Applications of Composites - Justification*

Applications of advanced composites, especially carbon fibre containing composites are justified on the following grounds:

- Combination of light weight, high modulus and superior strength.
- Good fatigue and corrosion resistance.
- Unique design possibility including ease of fabrication of complicated structures
- Reduced parts count and hence low inventory and assembly time
- Low energy requirements of production and Labour cost of processing

Advanced composites excel over their metallic counter parts, especially in specific modulus and strength. Since these criteria have a significant influence and fuel consumption of aerospace vehicles. Advanced composites are being extensively and justifiably used in aerospace areas rather than in other industries. The cost factor is a detterent for the latter.

VI. AEROSPACE APPLICATIONS

The last yet very important topic in my paper is this particular topic. Applications of these composites in aerospace engineering. Being an aerospace engineer I must be giving an layout of a/c (it's not air conditioner this is how we abbreviate aircraft) without possibilities of amalgamating the above explanations given regarding composites.

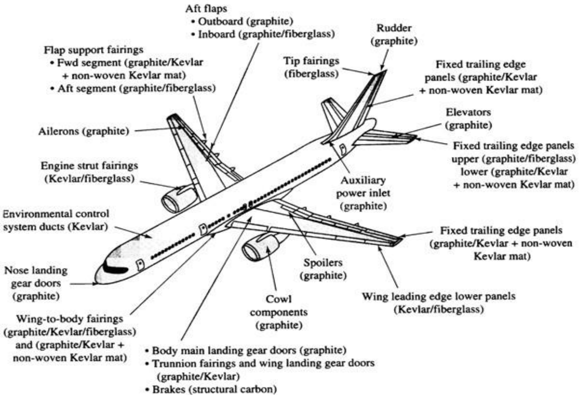


Figure 4 : Aircraft's layout

a) *Aircrafts and other air breathing vehicles which can be airborne*

Though the advanced composites in the construction of aircraft and helicopters, weight savings of 20-30% are achieved as compared to conventional materials. Fairings, landing gears, engine cowls, rudder, fin boxes, doors, floor boards and many other interior gadgets are made of advanced composites in combination with metallic and non metallic honey comb cores and metals. The recently launched prototype of Advanced Light Helicopter (ALH) is said to have as much as 60% of the surface area made up of composite components including advanced fibre components and metal sandwich structures.

b) *Space*

Two factors, high specific modulus and strength, and dimensional stability during large changes in temperature in space make composites the material of choice in space applications. Examples include the graphite/epoxy-honeycomb payload bay doors in the space shuttle. Weight savings over conventional metal alloys translate to higher payloads which cost as much as \$1000/lb (\$2280/kg). also, for the space shuttles remote manipulator arm, which deploys and retrieves payloads, graphite/epoxy was chosen primary for weight savings and for small mechanical and thermal deflections. Antenna ribs and struts in satellite systems use graphite/epoxy for their high specific stiffness and its ability to meet the dimensional stability requirements due to large temperature excursions in space. Remember *"aerodynamic heating"* during reentry should also be taken into concern.

c) *Rocket and Missiles*

Rocket motor cases and liners are made using composites of carbon, aramid and glass. Formulated epoxies, phenolics and polyimide materials are being used. Carbon – carbon composites are used for re-entry nose tips and heat shields. These applications, which require a lower ablation rate, higher bulk density and superior mechanical strength, are possible with carbon-carbon composites compared to monolithic graphite. Carbon–carbon composite items are successfully made from 3-D fabrics followed by densification process.

VII. Conclusion

The material selection plays a very important role in the engineering. Almost everyone knows the story of *"TITANIC".* I am not discussing about the movie but the engineering behind the failure of the ship. Similarly there is one area which a lot of concentration in everything right from material selection to fabrication. Yes your thought is correct! it is Aerospace sector which needs a lot of care. Otherwise the consequences will be drastic.

In our country, although a lot of aerospace programmes have started using advanced composites, other industries are not aware of the development in this ever growing area of composite technology. This is due to lack of access to this technology and non implementation of the locally manufacturing prepegs at a reasonable cost. It is hoped that above the shortcomings will be overcome in the mere future!! Let the aerospace sector grow further by making use of this technology more and more.

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Principle of Quasi Work and its Import on Structural Analysis

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Abstract- Discrete structural models, as a basis for evolving a new design methodology, created the need for considering structural configuration as a variable. Existing energy methods and variational principles do not provide analysis link between pairs of structural configurations, whereas Principle of Quasi Work addresses this need. This is proved for discrete structural models by adapting Tellegen's theorem used in topologically similar electrical networks. Several forms of the basic theorem and derivatives of Principle of Quasi Work are deduced. Its import on structural analysis is examined. Examples of linear and nonlinear structural systems are included.

GJRE-D Classification : FOR Code: 090199

PRINCIPLEOFQUASIWORKANDITSIMPORTONSTRUCTURALANALYSIS

Strictly as per the compliance and regulations of :

Principle of Quasi Work and its Import on Structural Analysis

Inder Krishen Panditta

Abstract- Discrete structural models, as a basis for evolving a new design methodology, created the need for considering structural configuration as a variable. Existing energy methods and variational principles do not provide analysis link between pairs of structural configurations, whereas Principle of Quasi Work addresses this need. This is proved for discrete structural models by adapting Tellegen's theorem used in topologically similar electrical networks. Several forms of the basic theorem and derivatives of Principle of Quasi Work are deduced. Its import on structural analysis is examined. Examples of linear and nonlinear structural systems are included.

NOMENCLATURE

B = Total branch degrees of freedom

b_j = Total Degrees Of Freedom (DOF) associated with direction j.

$\{d\}_n$ = Nodal displacement in system 'n'.

F_i = Internal (branch) force.

$\{F\}_m$ = Set of internal forces in system 'm'.

$M_\#$ = Support moment reaction at support #.

m, n = Subscripts denoting topologically similar systems 'm' and 'n'.

N = Total degrees of freedom.

P_j = External (generalized) force.

$\{P\}_m$ = Self equilibrating set of external force acting on system 'm'.

$R_\#$ = Support reaction at support #.

S = Arbitrary parameter distributed over nodes.

U_{mn} = Quasi Strain Energy $(=\{F\}_m^T\{\delta\}_n)$

W_{mn} = Quasi Work $(=\{P\}_m^T\{d\}_n)$

ΔS_k = Difference of S between terminal nodes of branch k.

$\Gamma,\ \Lambda$ = Linear operators.

α = A constant.

$\{\delta\}_n$ = Set of compatible deformations in system 'n'.

π_{mn} = Quasi total potential.

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I. INTRODUCTION

Discrete structural element models characterizing stiffness, inertia and damping properties of structural elements forming the lower end of the spectrum of finite elements in evolving a new methodology termed as Model Based Design, MBD, was given by Prasad [1]. This method utilizes structural models as an assemblage of appropriately interconnected discrete elements or modules (comprising of such elements). The striking similarity between such discrete structural models and electrical networks led to the adaptation of concept of **T**opologically **S**imilar **S**ystems (TSS) in the realm of structural analysis by Pandita [2], Panditta, Ambardhar, et al [3], Panditta and Wani [4], Panditta, Shimpi, et al [5], Panditta [6] and Panditta [7].

However, during a search for the analytical methods suitable for providing an analysis link between a pair of TSS, a glaring inadequacy of the existing energy methods and variational principles is noticed. Exploitation of topological similarity for analysis is beyond the scope of existing energy methods (Argyris and Ashley [8] and Shames [9]), variational principles (Reissener [10,11]) and finite element methods (Cook, Malkus et al [12] and Akin [13]); since these principles/ methods can be applied only to one structural configuration at a time.

In this paper, general form of Principle of Quasi Work (PQW) and its derivatives based on Tellegen's theorem for electrical network analysis (Penfield, Spencer, et al [14]) governing a pair of TSS are derived and illustrated.

II. BASIC THEOREM

Equation for nodal equilibrium in direction 'j' of a discrete model of any structural system can be written as:

$$\sum_{i=1}^{b_j} F_i + P_j = 0 \tag{1}$$

Where, F_i is internal (branch) force, P_j is external (generalized) force and b_j represents total Degrees Of Freedom (DOF) associated with direction j.

Multiplication of left hand side of the above equation with any non-trivial nodal parameter will not alter the right hand side of this equation (even if the resulting product may not have any physical significance).

Hence, multiplying Eqn. (1) by any parameter S (distributed over the nodes) and taking the sum over all 'N' DOF of the system, one obtains:

$$\sum_{j=1}^{N}\left(\sum_{i=1}^{b_j} F_i S_j + P_j S_j\right) = 0 \qquad (2)$$

First term of the left hand side of Eqn. (2) takes the sum of the product over each branch twice (once on each node to which these branches are connected). This is equivalent to taking the sum of the product of the difference of S between terminal nodes of each branch (represented as ΔS) and the force due to this branch at one of the nodes. Hence, this double sum can be replaced by a single sum taken over all branches. Thus Eqn. (2) takes the form

$$\sum_{k=1}^{B} \mathrm{F_k}(\Delta \mathrm{S_k}) - \sum_{j=1}^{N} P_j S_j = 0 \qquad (3)$$

Where, $B = \sum_{j=1}^{N} b_j/2$.

Here, 'B' represents, in general, the total branch DOF of the structural system, ΔS_k is a branch parameter defined as the difference between the parameter values associated with the pair of the generalized directions corresponding to the k^th^ branch DOF and 'N' is the total number of DOF of the system.

The negative sign in Eqn. (3) is a consequence of the definition of F_k and ΔS_k together with the associated sign relevant to the self equilibrating force system in kth branch or more generally the kth branch DOF (in the sense that there can be more than one self equilibrating system of forces concurrently in the branch corresponding to tension, torsion, etc.).

Taking advantage of arbitrary nature of parameter S_j it will be prudent to define these S_j's as nodal parameters of another conveniently chosen TSS which could be distinctly different from the given structural system. Equation (3) can then be deduced to provide the mathematical statement of the basic theorem as:

$$\sum_{k=1}^{B}(F_k)_m\,(\Delta S_k)_n = \sum_{j=1}^{N}(P_j)_m\,(S_j)_n \qquad (4)$$

Where, the subscripts 'm' and 'n' refer to two distinct structural systems with topological similarity as their connecting link. This can also be stated as:

Sum of the product of internal branch forces of a system with the corresponding branch nodal parameter differences of another topologically similar system is equal to the sum of the product of external (self equilibrating) nodal forces of the system with corresponding nodal parameters of the topologically similar system.

Here, it may be relevant to mention that if *nodal parameter 'S_j'* is nodal displacement then the *product* has units of work/ energy and if it represents rate of nodal deformation then the *product* has units of power and so on.

Equation (4) can be written in matrix notation as:

$$\{F\}_m^T\{\Delta S\}_n - \{P\}_m^T\{S\}_n = 0 \qquad (5)$$

or

$$\Phi_{mn} = \phi_{mn} - \psi_{mn} = 0 \qquad (6)$$

Where, ϕ_{mn} represents the first term and ψ_{mn} second term in the left hand side of the Eqn.(5).

Even though, Eqn.(4), Eqn.(5), and Eqn.(6) are derived for systems where one deals with discrete set of finite nodes and branches, this theorem is equally applicable to continuous structures. Since continuum can be treated as consisting of infinite DOF and the above equations can be used for continuum by replacing vectors by functions and the vector products by integrals (over the appropriate domain) which represent the two terms in Eqn.(5). Each of the distribution functions can also be approximated by appropriate number of interpolation functions (i.e. generalised coordinates) and the resulting integrals of Eqn.(5) can also be represented by matrix products (e.g. as in FEM formulations). In fact, this equation is very wide in its scope and it can be applied to various fields of science. It only assumes the state of (static or dynamic) equilibrium for its applicability.

III. General form of Basic Theorem

Let Γ and Λ be two linear operators which when operated upon forces F and generalized parameters S of Eqn. (5), result in the most general form of the theorem:

$$\{\Gamma F\}^T\{\Delta(\Lambda S)\} = \{\Gamma P\}^T\{\Lambda S\} \qquad (7)$$

Above equation holds good for any type of element, loading/ excitation and boundary/ initial conditions. These operators when operated upon F and S should not change basic characteristics of F and S. These operators can be given a broader meaning which allows these operators to represent TSS also. For example let Γ, Λ represent TSS_m and TSS_n respectively, then Eqn. (7) reduces to Eqn. (5)

a) Weak Form

Interchanging the role of operators in Eqn.(7) we get:

$$\{\Lambda F\}^T\{\Delta(\Gamma S)\} = \{\Lambda P\}^T\{\Gamma S\} \qquad (8)$$

A linear combination of Eqns. (7) and (8) yields:

$$\begin{aligned}&\{\Gamma F\}^T\{\Delta(\Lambda S)\}+\alpha\{\Lambda F\}^T\{\Delta(\Gamma S)\}\\&=\{\Gamma P\}^T\{\Lambda S\}+\alpha\{\Lambda P\}^T\{\Gamma S\}\end{aligned}\qquad(9)$$

Where, α is any arbitrary constant. This equation is designated as the 'weak form' of the theorem. It will be useful when the theorem has to be applied twice.

b) Variational Form

Taking suitable variations over Eqn.(6) gives:

$$\delta[\Phi_{mn}]=0\qquad(10)$$

Since, force(s) F and parameter(s) S belong to two different systems, it is possible to vary a single parameter set of one of the systems at a time without affecting all other parameter sets. This formulation can have two variants owing to choice of TSS sequence (m and n). A brief illustration of the concept of TSS adapted to Structural mechanics follows.

IV. TOPOLOGICALLY SIMILAR SYSTEMS

To evolve the definition of topologically similar system, one has to go to Eqn. (3). In this equation second term is the summation over nodes hence, number of nodes in TSS should be same. First term of the equation is summed over braches hence number of branches should be same. As it also involves the parameter ΔS which in turn involves two nodes to which a branch is connected hence connectivity of branches should also be same. If one assures same interconnectivity of nodes it will in turn ensure that number of branches is same. Hence, for two systems to be topologically similar one has to ensure that total number of nodes is same and connectivity of branches is also same. Topology can now be defined as *unique layout of nodes with specified interconnectivity of nodes*. Systems with same topology are TSS.

Moreover, in the derivation of this equation the manner in which a branch force is developed is immaterial. Hence, systems with same topology (TSS) may differ in other details (e.g. material properties, boundary conditions, etc.). Illustrations of pairs of TSS for discrete structural models and continuum structures are given in Ref. [3]. For a given problem there are infinite number of TSS, wherein any branch/ element parameter can even assume limiting values of zero/ infinity (making such branch/ element on a load path vanish/ rigid)[3]. Conditions that continuum system should satisfy for being TSS have to be derived in each case. For beams and rods/ shafts conditions have been derived in Panditta, Ambardhar, et al. [3] and Panditta and Maruf [4], respectively.

Obtaining equations that can link such systems would be a boon for structural analysis. If one succeeds in this crucial step, all advantages of the structural analysis theorems available for the solution of a single system can now be extended to an unlimited group of structures which have topological similarity as their link (and the only constraint in their choice).

Now, the energy principle (PQW) applicable to a pair of *topologically similar structural systems* will be deduced from the basic theorem.

V. PRINCIPAL OF QUASI WORK

If generalized parameters $(S_j)_n$ in the Basic theorem are replaced by generalized displacements $(d_j)_n$ of TSS_n, the following Principle of Quasi Work results:

In a pair of TSS, quasi work done by (self equilibrating set of) external forces of any one of the systems while going through the ***corresponding*** *(compatible) displacements of the other system, is equal to quasi energy due to internal forces of former system while going through* ***corresponding*** *deformations of the latter system.*

In the mathematical form it can be stated as:

$$W_{mn}=U_{mn}\qquad(11)$$

In case of continuum systems, quasi energy is computed by utilising stresses of one system and strains of other system.

a) Proof

By replacing $\{S\}_n$ by displacements $\{d\}_n$ and branch parameters $\{\Delta S\}_n$ by branch deformations $\{\delta\}_n$, equation (5) becomes:

$$\{P\}_m^T\{d\}_n=\{F\}_m^T\{\delta\}_n\qquad(12)$$

And, hence, Eqn.(11) is proved.

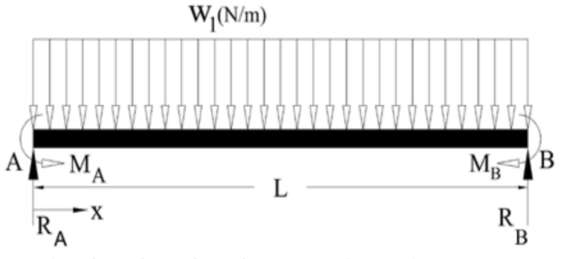
Panditta, Shimpi, et al. [5] validated PQW and derived useful theorems based on PQW for discrete structural models. Panditta, Ambardhar, et al. [3] after validating PQW for beams applied it to redundant beams with advantage. Panditta and Maruf [4] applied PQW to one dimensional structural elements for getting deflection without resorting to internal force/ moment distributions. Panditta [6] used PQW for calculating nodal deflection of trusses with great advantage and Panditta [7] applied PQW to columns for obtaining Euler critical load without resorting to the solution of differential equations. In the next section direct application of PQW to indeterminate structures is given.

VI. APPLICATION OF PQW TO INDETERMINATE STRUCTURE

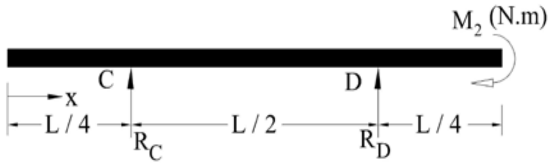
Figure 1a shows a uniformly loaded indeterminate beam built in at both the ends with length L and flexural rigidity E_1I_1. From symmetry and equilibrium considerations $R_A = R_B = w_1L/2$ and $M_A = M_B$. Hence, only unknown to be determined is either M_A or M_B. This given beam is designated as TES_1. In order to apply PQW, a pair of TES is needed. In this example, a simply supported beam with overhang on both the sides as given in Fig.1b is selected as TES_2. TES are topologically equivalent systems in which $E_1 I_1 = E_2 I_2 = EI$ (for beams). Quasi energy U_{21} and quasi work W_{21} for this pair is given by:

$$\begin{aligned} U_{21} &= M_2\, L\,(12\, M_A - w_1\, L^2)/24\, EI \\ W_{21} &= \{R_C\}_2\{v(L/4)\}_1 + \{R_D\}_2\{v(3L/4)\}_1 \\ &\quad + \{M_2\}_2\{v'(L)\}_1 = 0 \end{aligned} \tag{13}$$

$W_{21} = 0$ as reactions $R_C = - R_D$ in TSS_2 and in TSS_1 deflections v (L/4) = v (3L/4) due to symmetry and v' (L) = 0. Applying PQW (i.e. $U_{12} = W_{12}$), one gets MA = MB = $wL^2/12$. It can be seen from this simple example that PQW connects two distinct structural systems and provides solution for one system using the solution of other system. This is not possible through conventional theorems unless the later beam is a statically determinate part of the given problem, which is not the case in the present example.



a) Fixed - Fixed Beam $(TSS)_1$



b) Beam with Overhangs $(TSS)_2$

Figure 1 : Beam with both ends built - in

VII. THEOREMS BASED ON PQW

Counterpart of some of the well known energy theorems which will be applicable to TSS will now be derived from PQW. Pandita [6] has obtained deflection theorem, load theorem (counterparts of Castigliano's theorems) and unit load theorem for TSS and has also derived relative displacement theorem and its two corollaries which make calculation of nodal deflections of trusses very easy. Relative displacement theorem[6] does not have its counterpart in structural analysis. Equivalent forms of some other conventional theorems are given below:

a) Variational Principles for TSS

Variational principles applicable to topologically similar systems can be derived by considering variational form of Eqn. (11):

$$\delta(U_{mn} - W_{mn}) = \delta\pi_{mn} = 0 \tag{14}$$

$$\text{i.e}\ \sum_{j=1}^{N} \frac{\partial \pi_{mn}}{\partial d_{jn}}\ \delta d_{jn} + \sum_{k=1}^{B} \frac{\partial \pi_{mn}}{\partial P_{jm}}\ \delta P_{jm} = 0 \tag{15}$$

Where, π_{mn} is the quasi total potential.

Making an appropriate choice of variations, either in forces or in displacements, Eqn.(14) gives rise to:

$$\frac{\partial}{\partial d_{jn}}[\pi_{mn}] = 0 \tag{16}$$

$$\text{or}\quad \frac{\partial}{\partial P_{jm}}[\pi_{mn}] = 0 \tag{17}$$

It may be relevant to state that Eqns.(16) and (17) in respect of Topologically identical systems (when m=n) correspond to the familiar variational principles with the significant difference that π_{mn} should be replaced by the total complementary potential energy.

Unlike in the concept of total potential where one considers only applied loads and ignores reactions due to constraints which do no work, in the present context both applied forces and constraint reactions have to be considered, since the displacement field of the TSS can contribute to work terms due to reactions. Here, the total quasi potential becomes zero which is not the case of the total potential where the condition of its stationary value generates the necessary equations.

In Eqns.(16) and (17), the term 'virtual' is conspicuous by its absence as here one deals with real displacements and real forces. Since, both forces $\{P\}_m$ and displacements $\{d\}_n$ are independent of each other (as these belong to different systems), it is possible to obtain variations with either of these. For the same reason, even the use of the term 'complementary energy' does not find a place in these formulations/ theorems.

b) Reciprocal Flexibility Theorem for TSS

Consider a pair of topologically similar systems TSS_m and TSS_n with corresponding pair of directions i and j specified within each of these systems.

For a pair of global directions (i and j) defined in each of the given pair of TSS_m and TSS_n; ratio of $\bar{d}_{jm}$ (displacement in direction j due to a unit load in direction i of TSS_m) and $\bar{d}_{in}$ is directly proportional to ratio of their respective generalized reciprocal flexibilities $(f_{ji})_m$ and *$(f_{ij})_n$ corresponding to the pair of directions.* Mathematically, this can be stated as:

$$\frac{\bar{d}_{jm}}{\bar{d}_{jn}} = \frac{(f_{ji})_m}{(f_{ij})_n} \tag{18}$$

i. *Proof*

From the definition of flexibility coefficients f_{ij} with respect to a pair of global generalized directions *i* and *j* for a pair of TSS, the displacements in directions j and i in system m and n respectively are given by:

$$d_{jm} = (f_{ji})_m \; P_{im} \tag{19}$$

$$d_{in} = (f_{ij})_n \; P_{jn} \tag{20}$$

By dividing these equations and substituting $P_{im}=P_{jn}=1$, one obtains Eqn.(18) which reduces to Reciprocal Theorem (i.e. $f_{ij}=f_{ji}$), when the pair of systems is identical.

VIII. Application of PQW to Nonlinear Structure

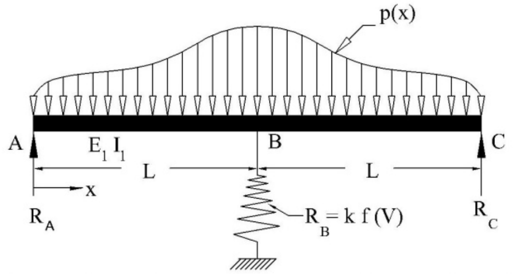
Application of PQW and its derivative theorems are given Ref. [3-7] for discrete models[5] and linear structures. In this section, an example is included to illustrate application of deflection theorem[6] to a typical nonlinear structure.

a) Illustration: A Typical Nonlinear Structure

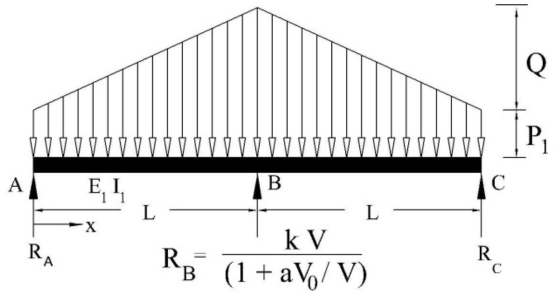
Equation for mid span deflection of a simply supported beam with a nonlinear elastic prop at the centre and subjected to a general case of transverse loading (vide Fig.2a) will now be obtained. Here, nonlinear characteristic of the prop are chosen to be the same as those used in Argyris and Kelsey [8] while illustrating the principle of virtual displacement. A typical symmetric load distribution as in Fig. 2b is chosen to get expression for mid span deflection as given in Ref. 8, as a special case there of.

For this purpose, a TSS_2 is chosen as in Fig 1c, here, it is termed as TES_2 by taking $E_2I_2 = E_1I_1 = EI$. Displacement of TES_2 can be written as:

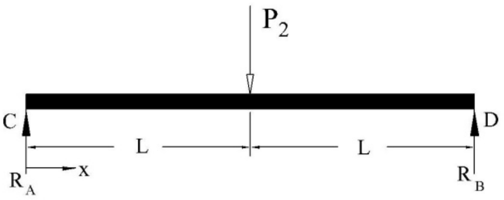
$$\begin{aligned} v_2(x) &= P_2(x^3 - 2 < x - L >^3 - 3L^2 x)/12EI \\ &= P_2\, \bar{v}_2(x) \quad \text{and} \\ v_2(L) &= -P_2 L^3/6EI = -P_2 \beta / k \\ \text{where} \quad \beta &= k\, L^3/6EI \end{aligned} \tag{21}$$



a) Nonlinear Structure- General Case $(TSS)_1$



b) Nonlinear Structure - Particular Case $(TES)_1$



c) Simply Supported Beam $(TSS)_2$

Figure 2 : Indeterminate Beam on a nonlinear support

The quasi work W_{12} is given by:

$$\begin{aligned} W_{12} &= \int_0^{2L} \{p(x)\}_1 \, \{P_2 \bar{v}_2(x)\}_2 \, dx \\ &\quad + \{R_B\}_2 \, \{P_2 \, \bar{v}_2(L)\}_2 \\ &= \{P_2\}_2 \, [V_1 + R_B \, \bar{v}_2(L)] \end{aligned} \tag{22}$$

$$\text{where, } V_1 = \int_0^{2L} p(x)\, \bar{v}_2(x)\, dx \quad \text{and}$$

$$\bar{v}_2(L) = v_2(L)/P_2 = -\beta/k$$

The deflection V at x = L of TES_1 is:

$$V = \partial W_{12} / \partial \{P_2\}_2 = V_1 - \beta f(V) \tag{23}$$

Substituting f (V) = V [1+ a / (1 – V / V_0)] (vide Fig. 1b, where V_0 is the limiting deformation of the prop) yields the following quadratic equation:

$$\begin{aligned} &(1+\beta)\,(V/V_0)^2 - [1+\beta\,(1+a) \\ &+ V_1/V_0]\,(V/V_0) + V_1/V_0 = 0 \end{aligned} \tag{24}$$

The value of V_1 can be calculated for any given loading p(x). For the typical symmetrical linear load distribution shown in Fig. 1b, we get:

$$V_1 = \frac{5P_1L^4}{24EI} + \frac{2QL^5}{15EI} \qquad (25)$$

It may be noted that Q = 0 results in an expression for V which is identical to the one given in Ref. [8], page 10.

IX. Import on Structural Analysis

Introduction of this Principle of Quasi Work (PQW), in the realm of structural mechanics heralds a new phase of structural analysis and has the following unique features:

a) Conventional energy theorems and variational principles are special cases of PQW and its derivatives respectively. Hence, this principle has far reaching utility.

b) It incorporates the advantages of both the force and displacement analysis procedures and unifies these distinct procedures.

c) It dispenses with the concept of '*virtual displacement*', '*virtual force*' and '*complimentary energy*'.

d) It offers simpler procedures for redundant structural analysis.

X. Conclusions

- A new theorem in its various forms has been derived. Though, this theorem has potential for application in several fields, this paper addresses its applications to the field of structural analysis through Principle of Quasi Work.
- PQW has the distinction of being able to form a link between any two distinct topologically similar structural systems, thereby, offering a wide choice for solving complex structural problems. Such a link, for the first time, has paved way for solution of many a problem with the help of the solution of a suitably chosen topologically similar problem. This has made it possible to have new procedures for analysis of statically indeterminate structures.
- Conventional energy/ variational principles fall out as a special case of PQW and its derivatives.
- PQW dispenses with the concepts of virtual displacements, virtual forces and complementary energy.
- Utility of PQW through its various derivatives is demonstrated by its application to nonlinear structures.
- Versatility of PQW stands already established by various authors through applications to discrete and linear continuum structures.

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Aerodynamic Characteristics of a Real 3D Flow around a Finite Wing

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MLR Institute of Technology, India

Abstract- This paper presents a new method of solution for the aerodynamics of finite-span wings, which overcomes the difficulties of the previous methods. A lot of disturbance is created in the air when an aeroplane flies. It is through the study of these disturbances of the flow past the airfoil, lots of design considerations are done. In this paper, we design a 3D air wing and solve the flow equations in a CFD solver and study the characteristics features of the flow around a finite wing and the effect of the tip vortices that are caused by the difference of pressures between the lower and upper portion around the tips on an air airfoil.

Keywords: finite wing, real 3d flow, vortices, pressure differences, vortex flow.

GJRE-D Classification : FOR Code: 090101

AERODYNAMICCHARACTERISTICSOFAREAL3DFLOWAROUNDAFINITEWING

Aerodynamic Characteristics of a Real 3D Flow around a Finite Wing

Sanjay Kumar Sardiwal [α], Md. Abdul Sami [σ], B. V. Sai Anoop [ρ], Syed Arshad Uddin [ω], Gudipudi Susmita [¥] & Lahari Vooturi [§]

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I. Introduction

An airfoil is the shape of a wing or blade (of a propeller, rotor or turbine) as seen in cross-section.

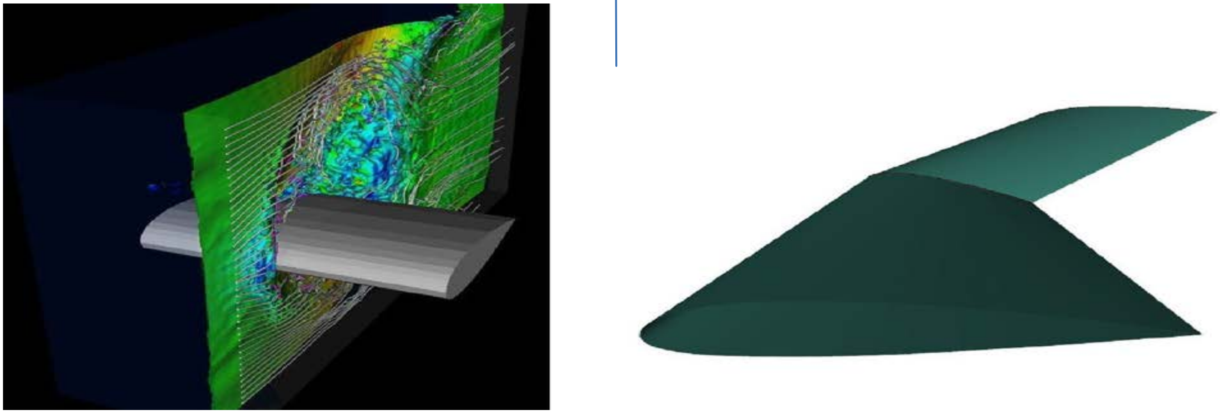

Figure 1 : Cross-section of a wing

The design and analysis of the wings of aircraft is one of the principal applications of the science of aerodynamics, which is a branch of fluid mechanics. Little modification in the airfoil has a direct impact on the performance of an aircraft.

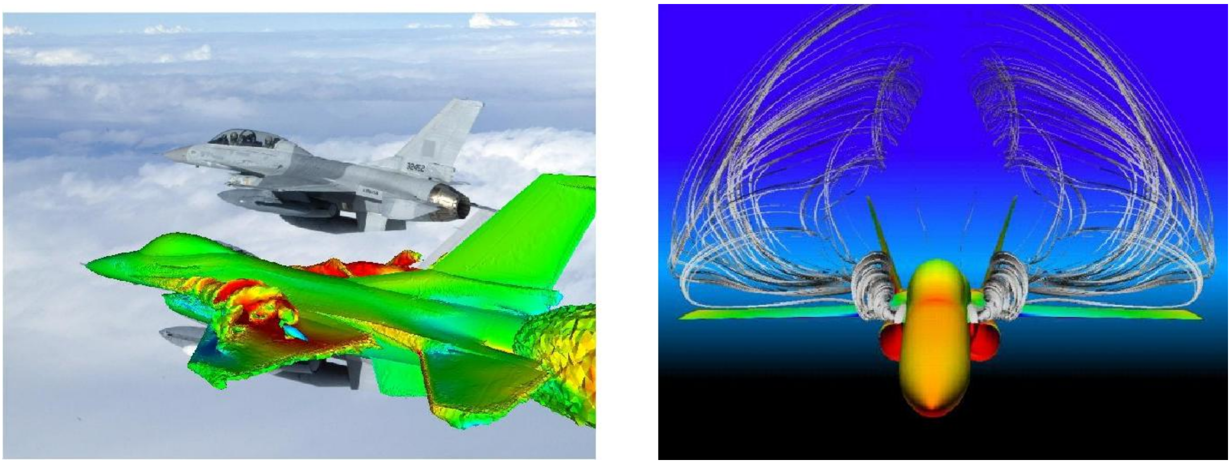

Figure 2 : Visualization of vortex flow past an aircraft

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Author ω : Department of Aeronautical Engineering, Malla Reddy College of Engineering and Technology, Hyderabad.

Here, we design a 3D air wing and solve the flow equations in a CFD solver and study the characteristics features of the flow around a finite wing and the effect of the tip vortices that are caused by the difference of pressures between the lower and upper portion around the tips on an air airfoil. Better visualization of this vortex flow past an aircraft helps in optimizing the design of a wing.

II. DISTURBANCE OF FLOW PAST AIRFOIL

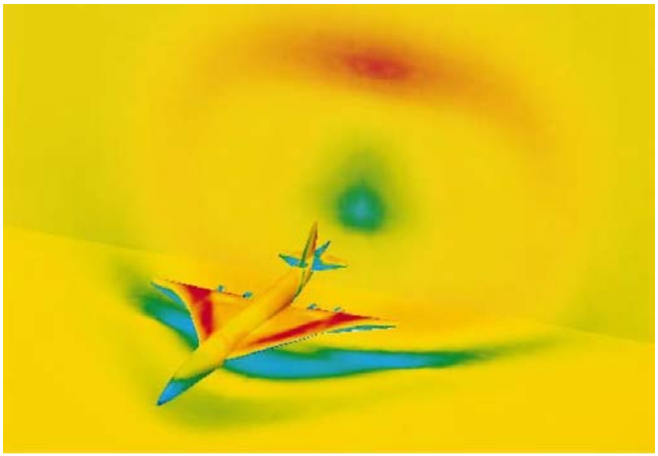


Figure 3 : Disturbances created on an aircraft

A lot of disturbance is created in the air when an aeroplane flies. It is through the study of these disturbances of the flow past the airfoil, lots of design considerations are done. Performance of the aeroplane is directly related to the size & shape of airfoil. A considerable difference is seen between the airfoil of the commercial airlines and the defense plane as most of the time better optimized airfoil leads to bad fuel consumption because of the huge drag and vice versa.

III. DESIGN, DATA GENERATION AND VISUALIZATION

Some of the important works done on Airfoils have been studied before solving this problem. This paper serves as a basis for understanding, designing and solving the flow problem.

A detail of the literature survey done has been included in the references list.

The Ansys workbench has a comprehensive list of software for doing various Structural and Fluid analysis and is also equipped with superior visualization capabilities which are in par with any other dedicated visualization software's. This workbench has been used for designing, solving and visualizing the results.

Execution of the Project:

The project is executed in three phases.

- Pre-processing
    - Design of the model is done using Sumo-2.4.1 and Design Modeler
    - Meshing the model in Ansys workbench
- Solving
    - Solving using CFD package Ansys Fluent
- Post-Processing
    - Analyzing the results using various visualizations
    - Interpreting the results

a) Pre-Processing

The design of the air wing is done using SUMO 2.4.1 and the wing is imported into Design Modeler to create far field.

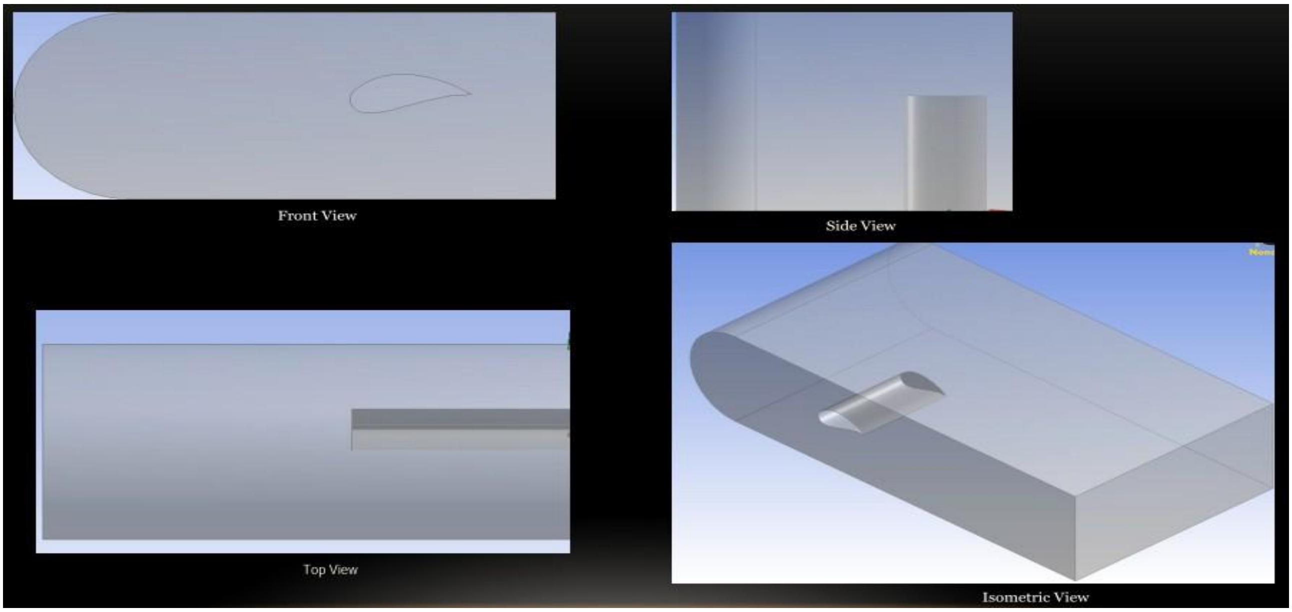


Figure 4 : CAD model of the 3d Air wing with the far field-

A medium size mesh is used for meshing purpose. A refinement of the mesh is done near the wing region as it is the focus of our interest.

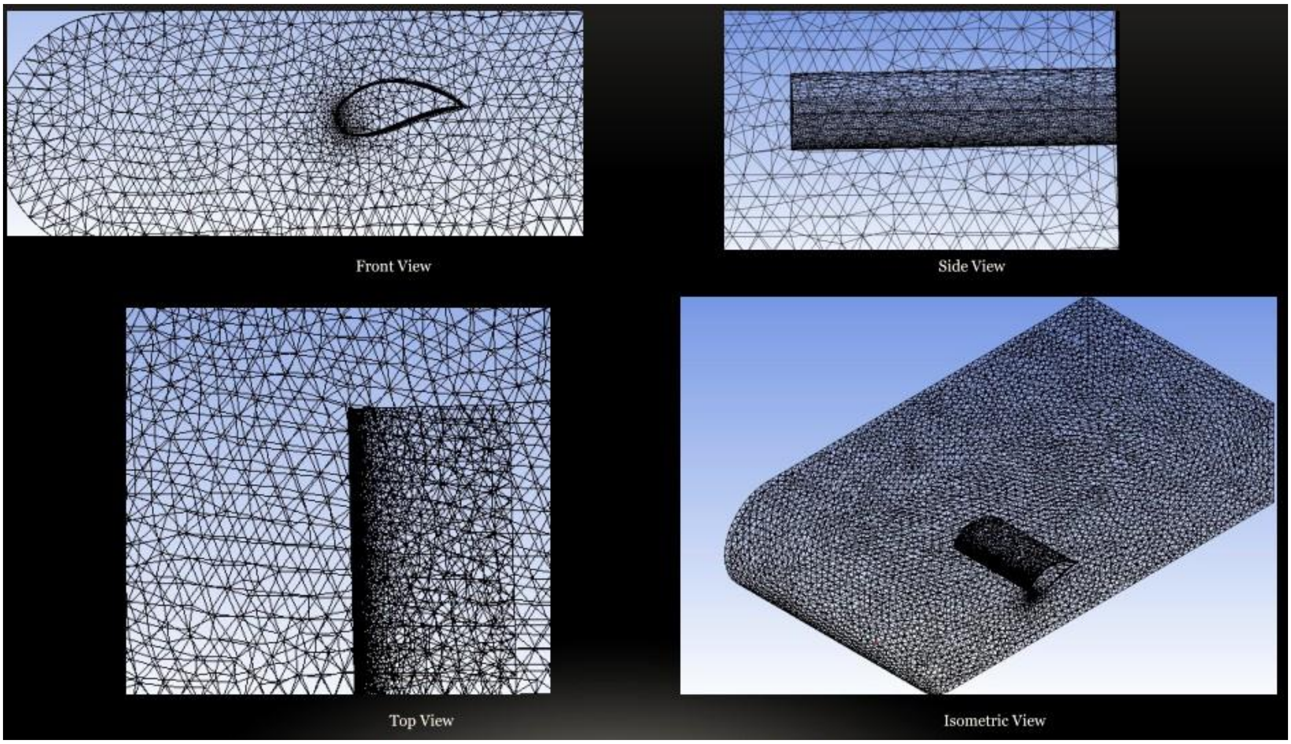


Figure 5 : Mesh of the entire domain

b) Solving

In the next phase, the various parameters of the flow is assigned to the model and also the boundary conditions are set and is solved using the CFD solver in Ansys Fluent.

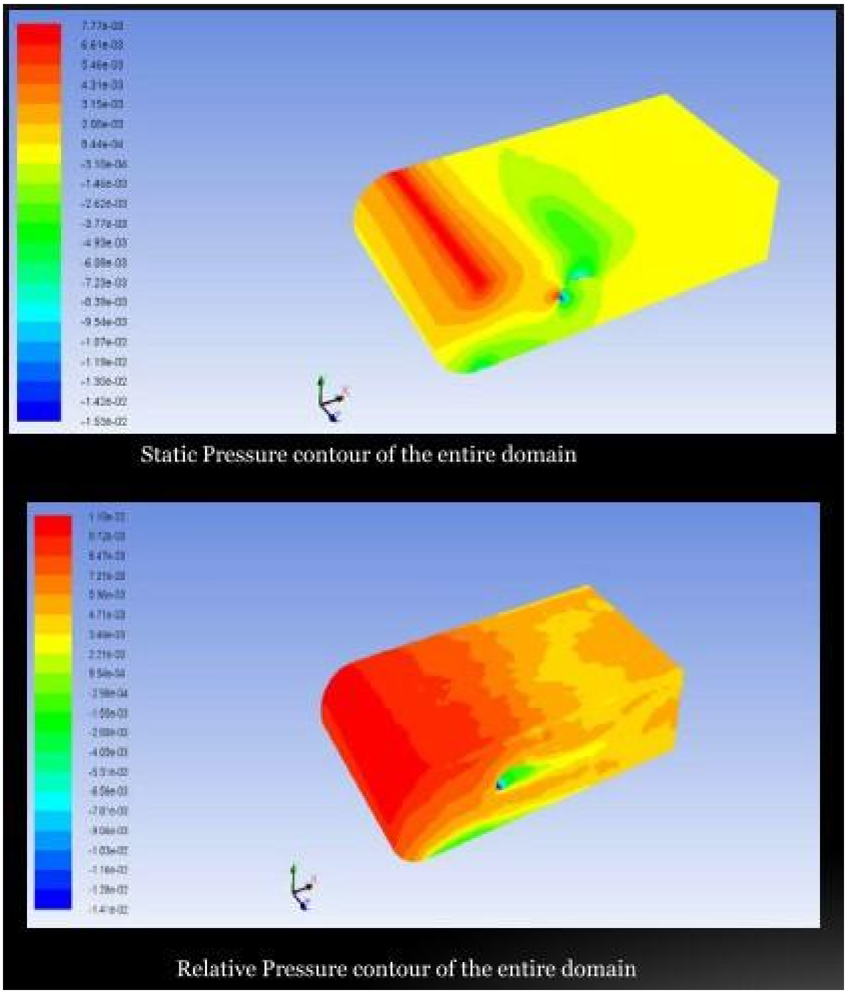
The following are the details of the flow:

- Flow type: Inviscid Flow
- Solver Type: Pressure Based
- Discretization Method: Finite Volume Discretization
- P-V coupling: SIMPLE Algorithm
- Turbulence: Spalart-Allmaras (1 equation)

c) Post-Processing

From the data that is generated, the flow is visualized using various visualization tools like contours, vector visualizations, particle tracing etc.

IV. Results



Static Pressure contour of the entire domain

Relative Pressure contour of the entire domain

Figure 6 : Static Pressure and Relative Pressure Contour of the entire domain

From the above visualization, we cannot make any worthwhile inferences or analysis. This is a crude data result and we need more refine visualization techniques.

a) Slicing of the Pressure Contour

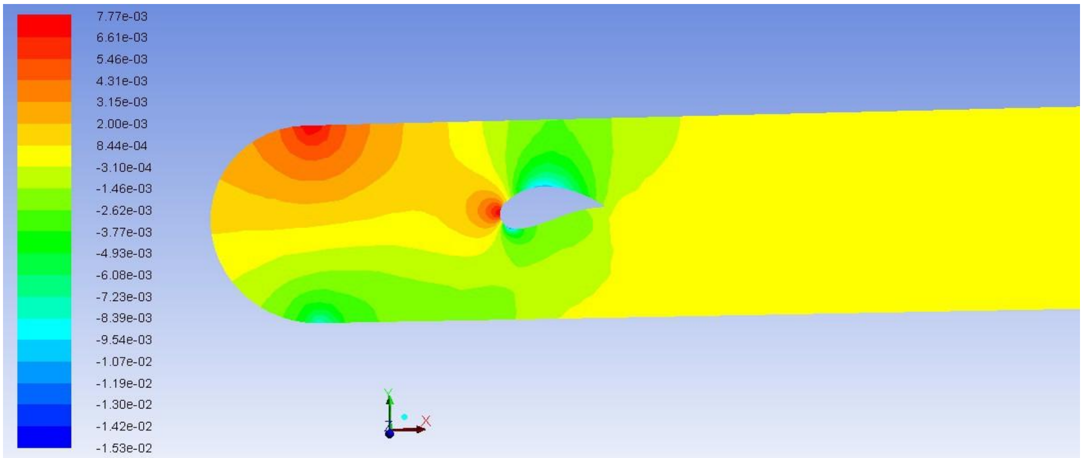


Figure 7 : Static Pressure contour from the XY Plane

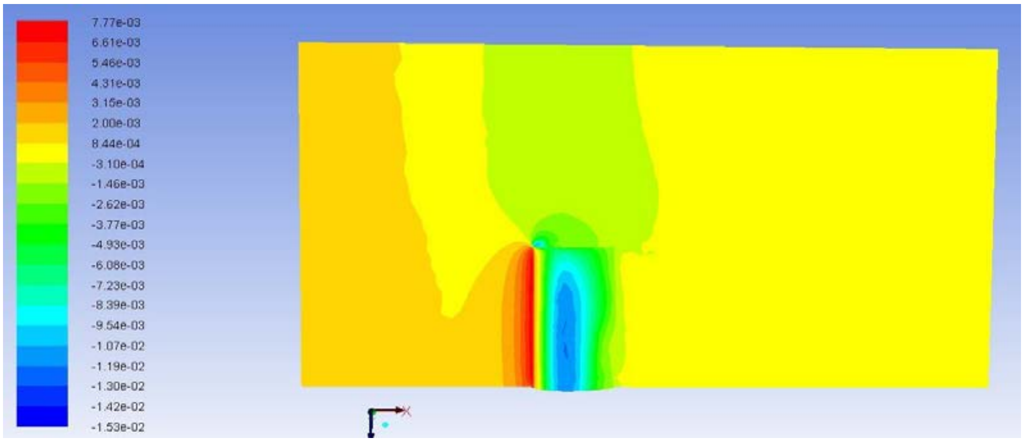


Figure 8 : Static Pressure contour from the XZ Plane

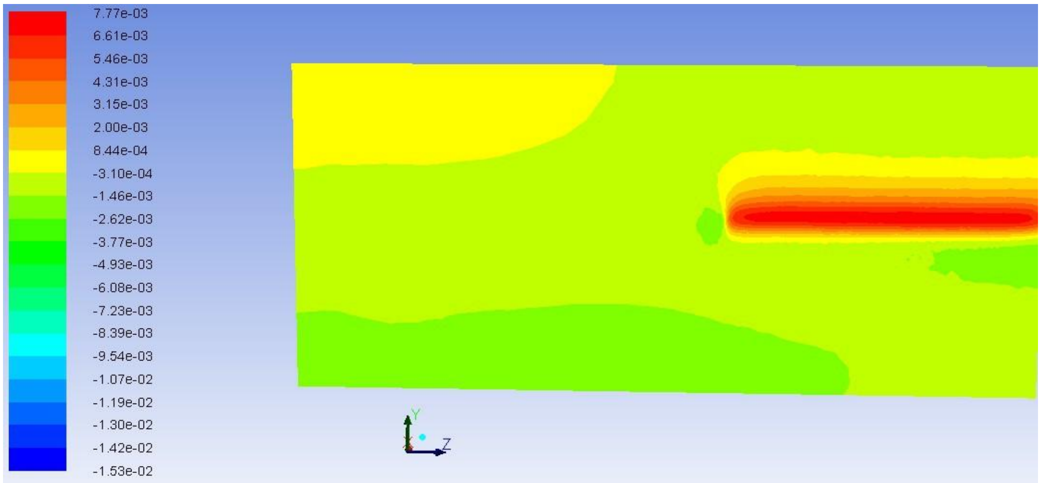


Figure 9 : Static Pressure contour from the YZ Plane

We sliced (cut) the model at the appropriate portion of our interest in all the three planes and we can now clearly see the pressure distribution across the wing. From the XZ plan we can observe that the pressure difference is caused by the effect of tip vortex.

b) Slicing of the Vectors

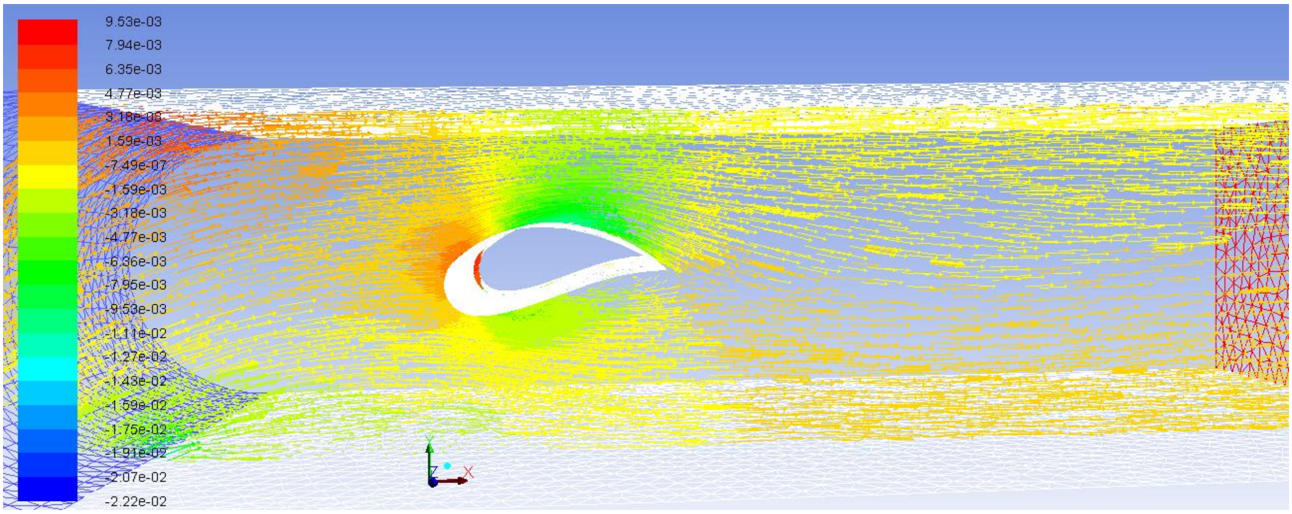


Figure 10 : Vector of the Pressure contour in XY Plane

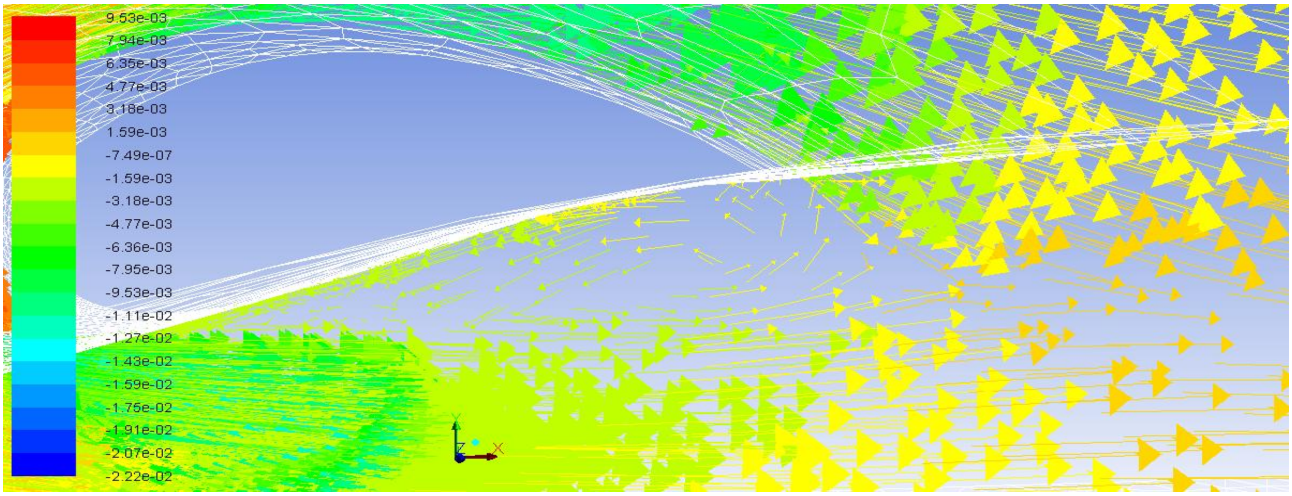


Figure 11 : Recirculation of the flow- XY Plane

From the above Vector visualization in XY plane we observe the recirculation of the flow at the trailing end of the airfoil. At small angles of attack, air flows smoothly around an airfoil providing lifting force through the difference in pressure across the top and bottom of the airfoil. As the angle of attack increases, the lift produced by the airfoil increases as well but only to a point.

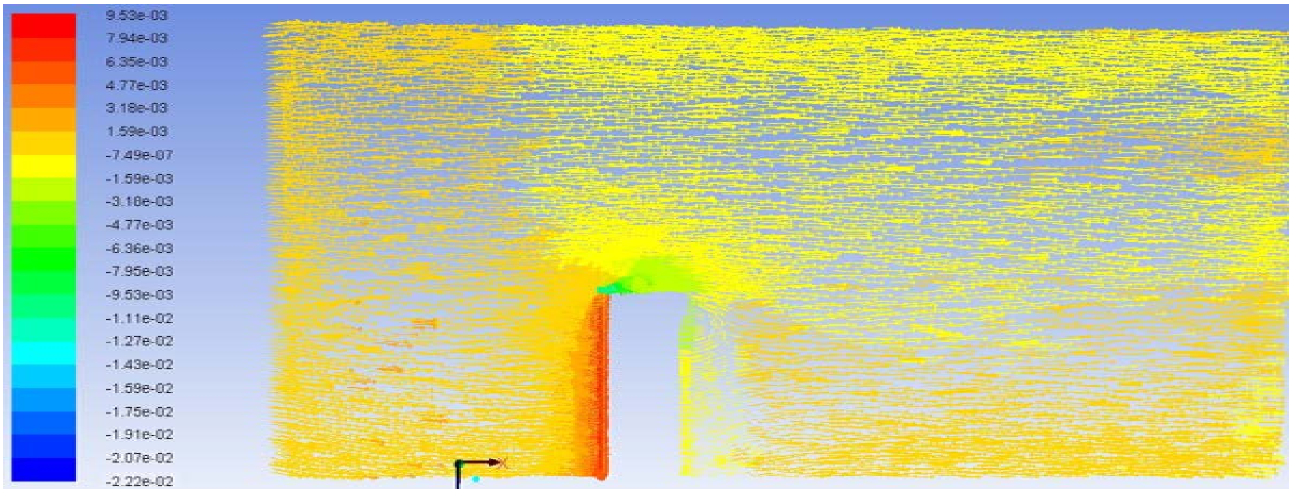


Figure 12 : Vector of the Pressure contour in XZ Plane

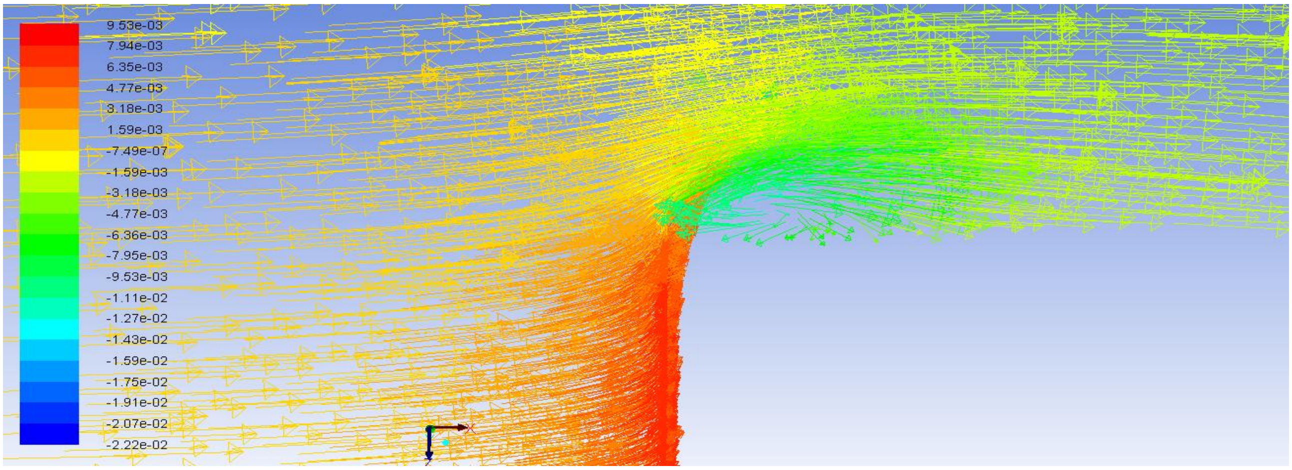


Figure 13 : Vector of the Pressure contour in XZ Plane

The tip vortices can be seen at the edge of the wing.

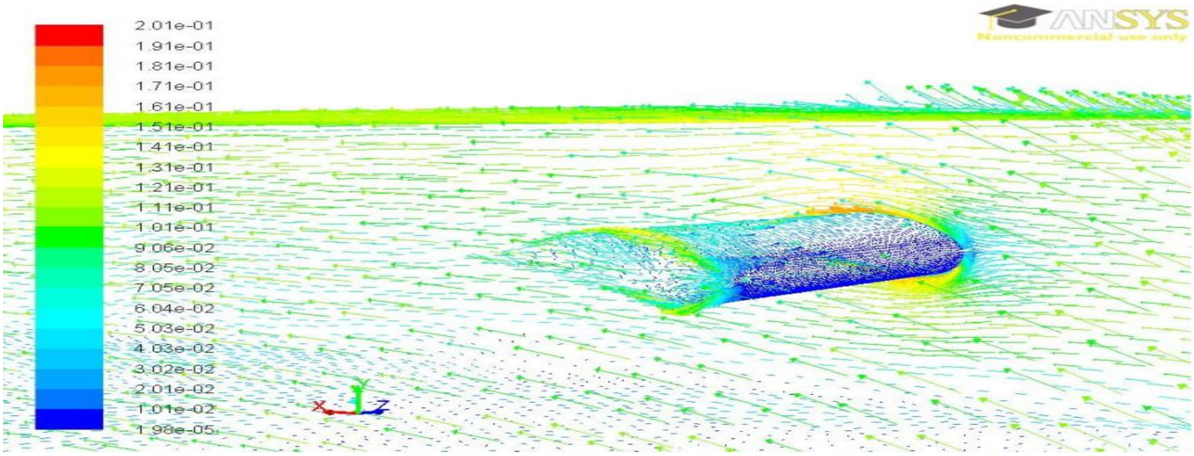


Figure 14 : Vector of the pressure contour of the 3d wing in Isometric view.

From the above figure we can clearly see that there are tip vortices which influence the drag of the airfoil

c) Other Display Options Used In Visualization

Listed below are some of the other visualization tools used in post-processing phase.

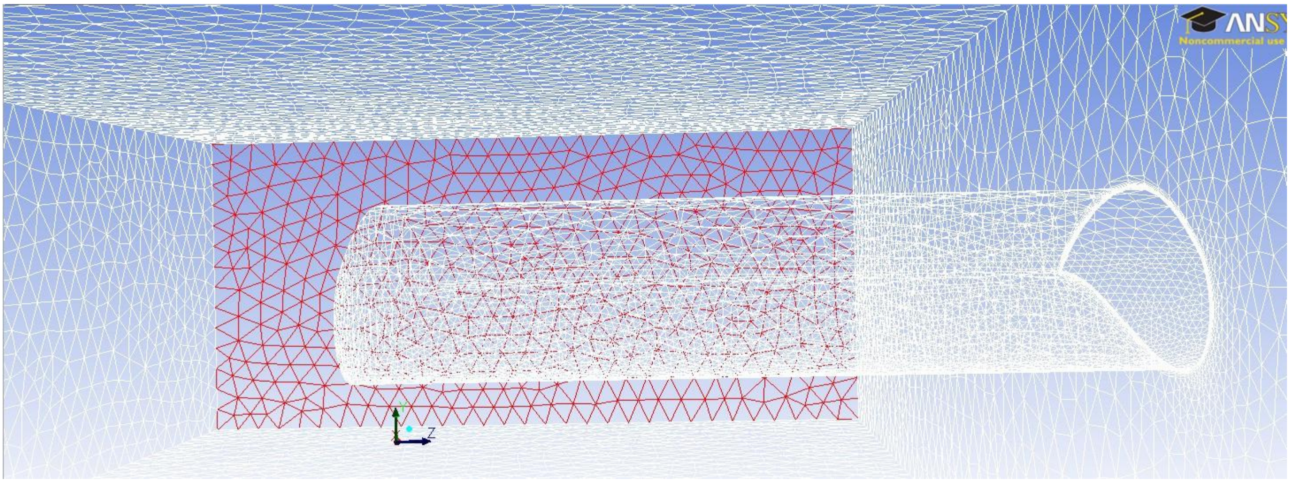


Figure 15 : 3D Wing Mesh in Ansys Fluent

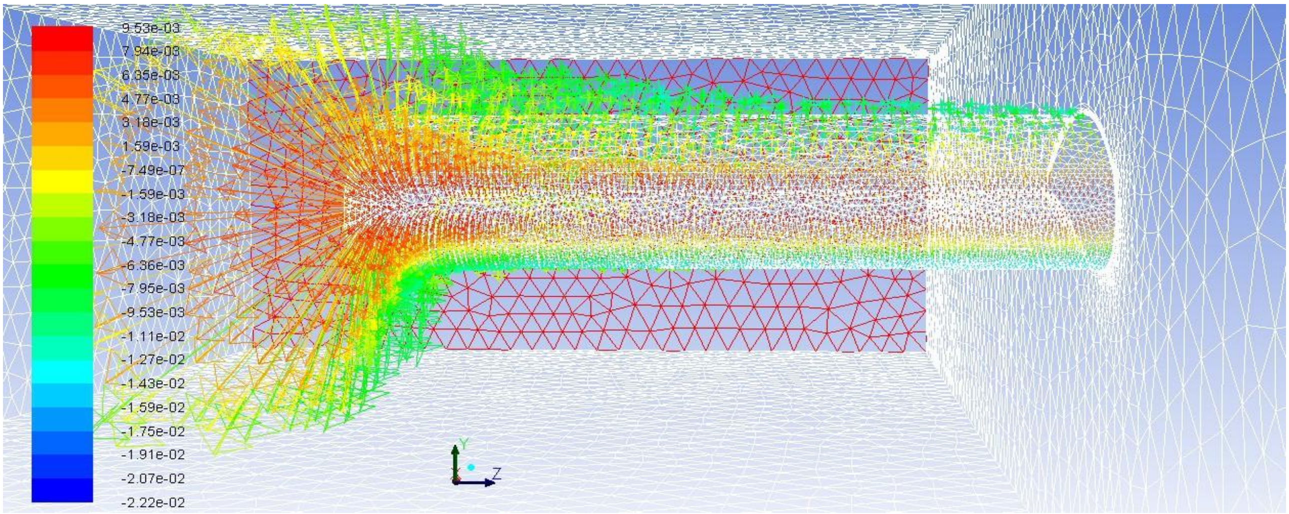


Figure 16 : 3D Wing vector of static pressure with mesh

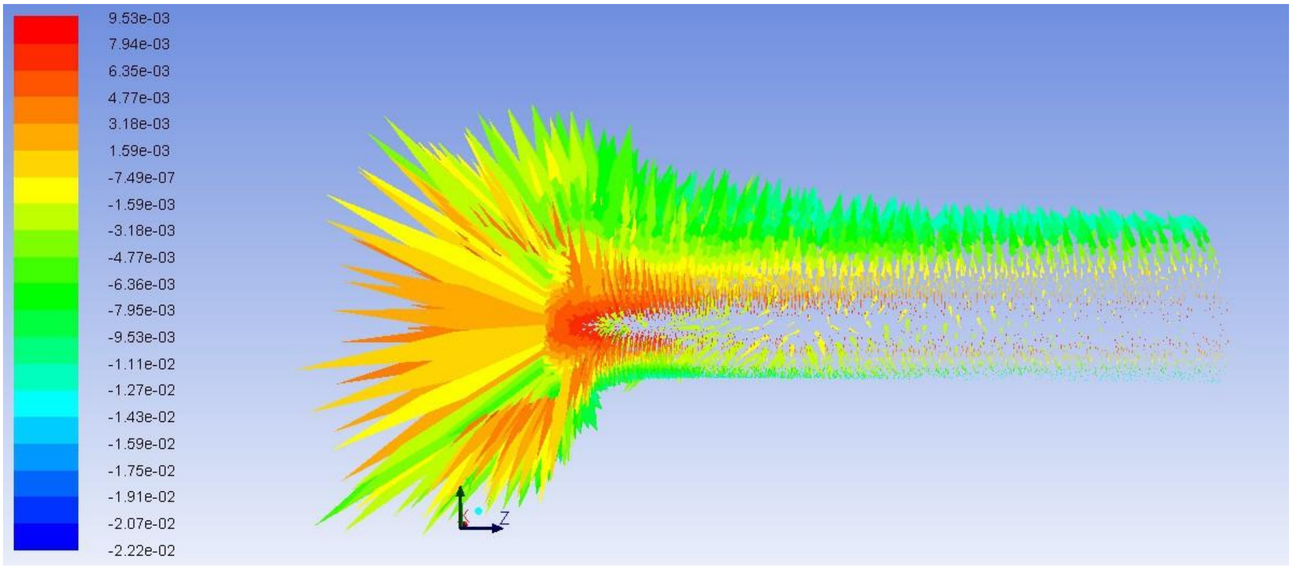


Figure 17 : 3D Wing vector of static pressure- Cone Options

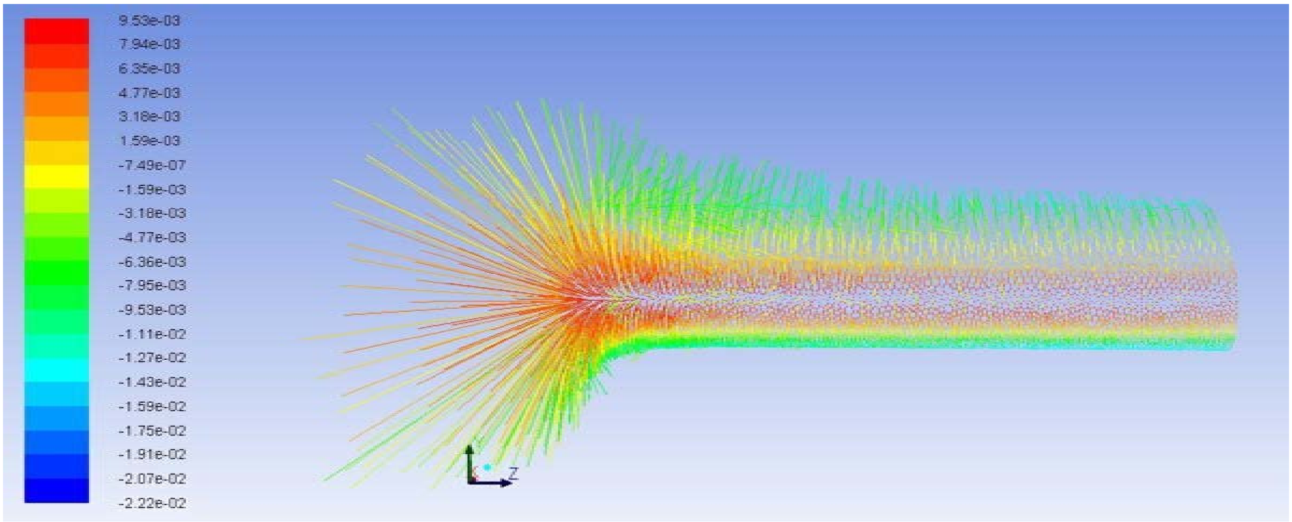


Figure 18 : 3D Wing vector of static pressure- headless option instead of arrows

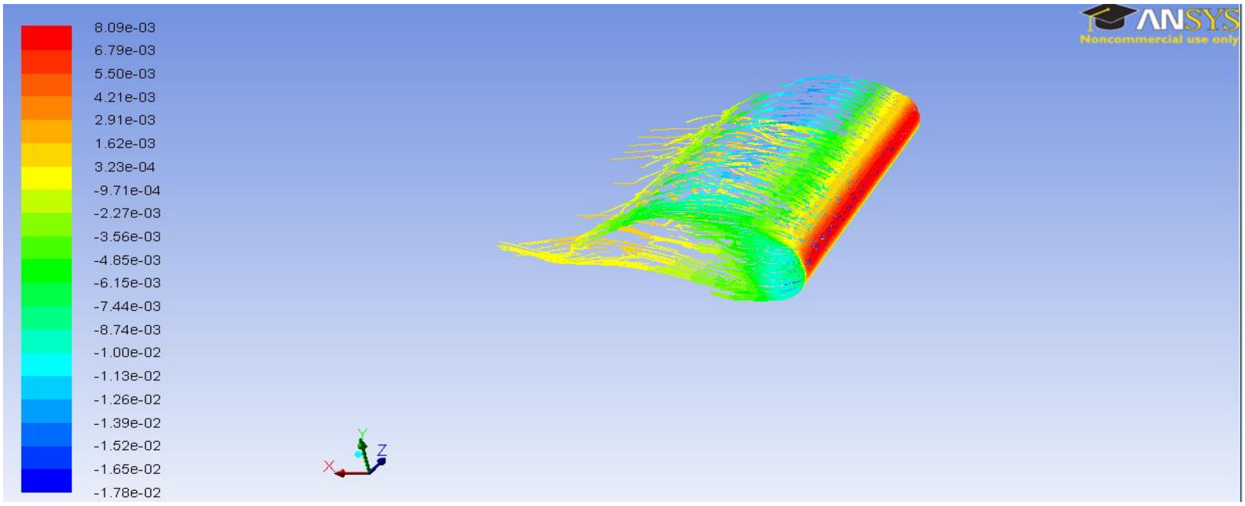


Figure 19 : 3D Wing Static pressure path lines

By understanding the data through various techniques of visualizations, we can modify the shape and size of the air wing to prevent the tip vortices from influencing the drag which impacts the performance of the aeroplane.

From slicing and through the methods like volume rendering, we can have animation of the flow.

d) Other Model Considered- Light Jet Executive

The Light Jet Executive has been modeled in SUMO 2.4.1 and the far field is modeled in Design Modeler.

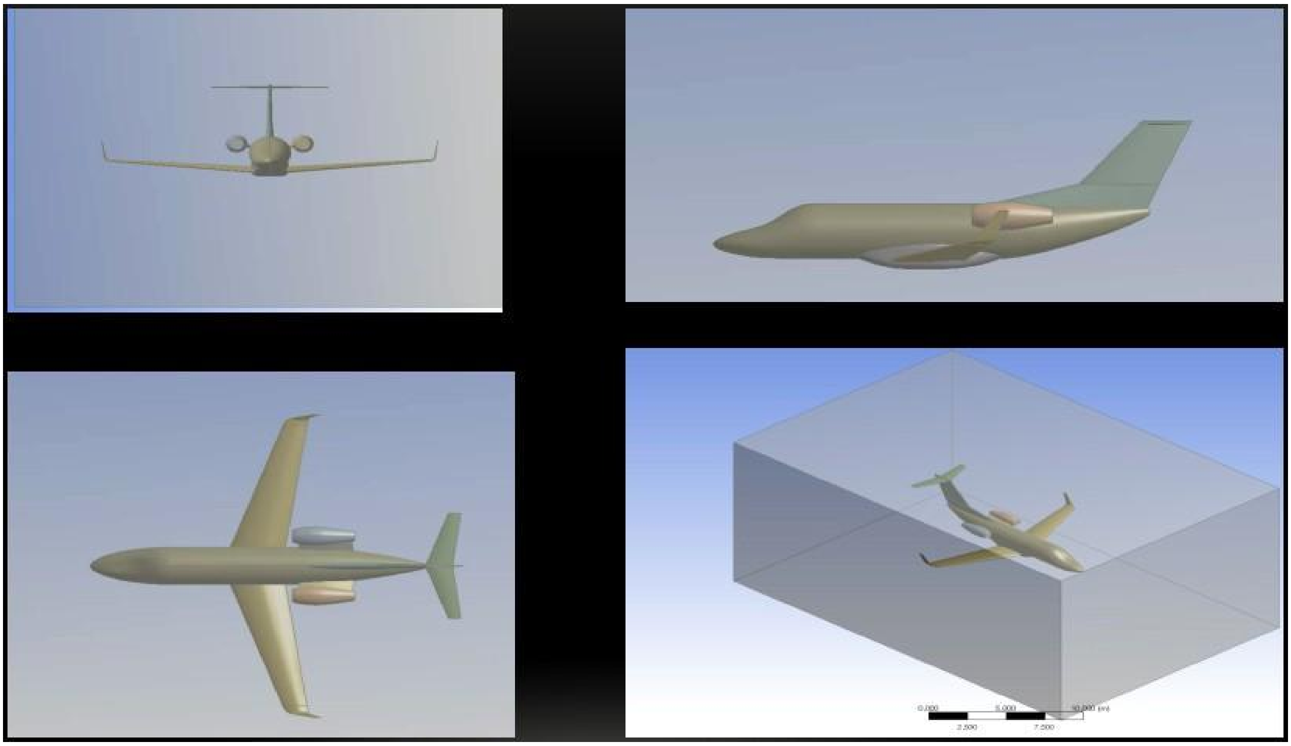


Figure 20 : Light Jet Executive CAD Model

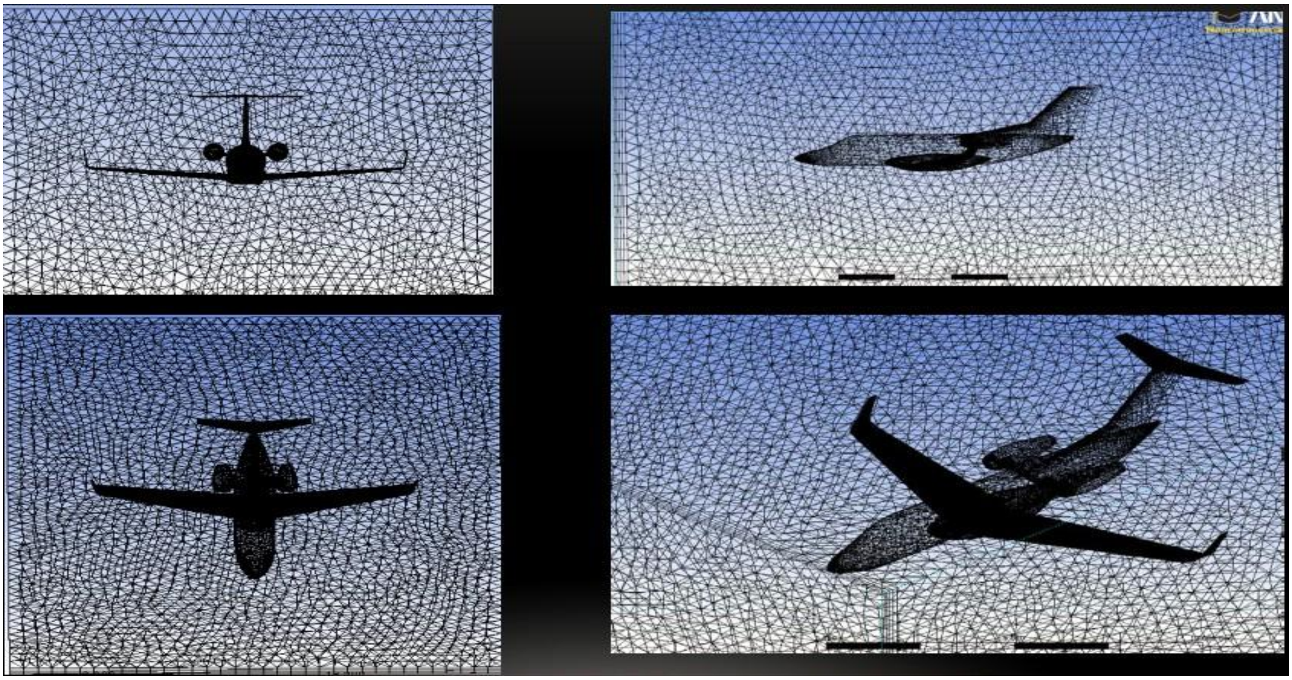


Figure 21 : Mesh of Light Jet Executive

Although the Light Jet Executive has been successfully modeled and meshed, there has been certain constraints due to which it could not be solved. Some of the major limitation were the problem with integrating the mesh of the far field with the Light Jet Executive.

Initial attempts to make the mesh very coarse were successful however solving the problem gave totally unrealistic results and was not stable.

V. Conclusions and Future Work

- The air wing and domain is modeled, meshed and solved and various post processing visualization options has been used for better understanding & investigation of the flow.
- Visualization options such as slicing and volume rendering proved extremely useful for doing the investigation of flow pattern.
- A better refinement of the mesh and boundary mesh and implementing better solvers can give accurate results for the 3D wing which can be potentially be validated with experimental results.
- An adaptive mesh refinement near the high gradients especially close to the wing gives more accurate results.
- Refinement of mesh and better meshing options required for solving Light Jet Executive Model.

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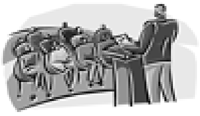

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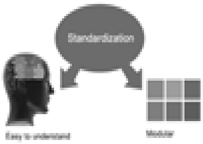

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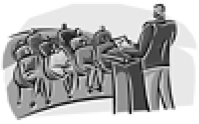

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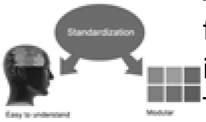

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- Consequences, including definite statistics - if the consequences are quantitative in nature, account quantitative data; results of any numerical analysis should be reported
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- Present a justification. Status your particular theory (es) or aim(s), and describe the logic that led you to choose them.
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Approach:

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- If use of a definite type of tools.
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The page length of this segment is set by the sum and types of data to be reported. Carry on to be to the point, by means of statistics and tables, if suitable, to present consequences most efficiently.You must obviously differentiate material that would usually be incorporated in a study editorial from any unprocessed data or additional appendix matter that would not be available. In fact, such matter should not be submitted at all except requested by the instructor.

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	A-B	**C-D**	**E-F**
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Introduction	Containing all background details with clear goal and appropriate details, flow specification, no grammar and spelling mistake, well organized sentence and paragraph, reference cited	Unclear and confusing data, appropriate format, grammar and spelling errors with unorganized matter	Out of place depth and content, hazy format
Methods and Procedures	Clear and to the point with well arranged paragraph, precision and accuracy of facts and figures, well organized subheads	Difficult to comprehend with embarrassed text, too much explanation but completed	Incorrect and unorganized structure with hazy meaning
Result	Well organized, Clear and specific, Correct units with precision, correct data, well structuring of paragraph, no grammar and spelling mistake	Complete and embarrassed text, difficult to comprehend	Irregular format with wrong facts and figures
Discussion	Well organized, meaningful specification, sound conclusion, logical and concise explanation, highly structured paragraph reference cited	Wordy, unclear conclusion, spurious	Conclusion is not cited, unorganized, difficult to comprehend
References	Complete and correct format, well organized	Beside the point, Incomplete	Wrong format and structuring

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