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Design, Analytical Analysis, Instrumentation and Flow Simulation of Sub-Sonic Open Circuit Wind Tunnel Model

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ABSTRACT: *The Wind Tunnel is well known for its enormous amount of potential in Civil, Environmental, Automobile and Aeronautical applications. In today's world, Everyone's main focus is to save time, material and money which have compelled us to opt for the experimental testing on scale models, before the final product is to be shaped. The Wind Tunnel is one such platform, which provides us the appropriate desired environment conditions around the model scaled to the compatible dimensions. Therefore, to develop the favorable conditions, the design of the tunnel plays the foremost role in its proper functioning. In this paper, knowing the intricacy of the tunnel's requirements, A Sub-Sonic Open Circuit Wind Tunnel (SOWT) Model is developed and simulated, having a Mach Number (M) of 0.15. The guiding dimensions taken for the Test Chamber are: Length (L_T) = 45cm, Height (H_T) = 18cm and Width (W_T) = 24cm with maximum operating speed to be 50m/s. Using these, the secondary design parameters were estimated and the design is finalized. Moreover, the instrumentation of the Tunnel including Data Acquisition Systems (DAQs) is reviewed.*

Keywords: *Sub Sonic Open Circuit Wind Tunnel, Mach number, Boundary Layer Modeling Parameters, Model Testing and Simulation.*

I. Introduction

Today, the wind tunnel is an indispensable part of development of modern aircraft, automobile etc as no one would contemplate committing an advanced design without first measuring its stability, lift and drag properties. The utility of the wind tunnel is obvious, but it was not the first aerodynamic test device. The quest to measure drag and various aspects of aviation theory started with the very first advancement in aviation with the introduction to whirling arm. The whirling arm apparatus (4 feet long) was developed by Benjamin Robins (1707-1751), a brilliant English mathematician. It spun by a falling weight acting on a pulley and spindle arrangement having velocities of only a few feet per second at the arm tip (top speeds ranging from 3 to 6 m/s). The large amount of turbulence posed serious problems in front of experimenters like in determination of the true relative velocity between the model and air. Also, it was difficult to mount the instruments and measure the small forces exerted on the model when it was spinning at high speeds. Francis Herbert Wenham (1824–1908), a council member of the Aeronautical Society of Great Britain, addressed the issue by inventing, designing and operating the first enclosed wind tunnel in 1871. After some of the experimental studies, it was found that lift-to-drag ratios were very high as such wings could support substantial loads, making powered flight which seemed much more attainable than previously thought possible. Further research work revealed the effect of what is now known as aspect ratio: long, narrow wings, like those on modern gliders, provided much more lift than stubby wings with the same areas [1-3].

Wilbur Wright (1867-1912) and Orville Wright (1871-1948) built their first flying machine in August 1899 and then their first unpowered manned glider in 1900. However, the glider was generating far less lift and more drag than they expected. They developed a simple experiment using natural winds to compare the relative lifting forces of flat and cambered surfaces. Then they built an aerodynamic balance that showed unambiguously, which test airfoil (among the two being tested) can develop more lift. Thus for the first time "Wind Tunnel without Walls" was subjected to test. It confirmed the accepted aerodynamic design tables that they were using, were seriously in error. This helped them in rectification of the wing area, airfoil curvature. During the experimental work, they reached at conclusion that without synthesizing a well equipped wind tunnel they could not continue their work anymore as such they developed the wind tunnel in its true sense and helped themselves to trigger the flight! [1, 4]

Wind tunnels are designed for a specific purpose and speed range. Therefore, there are different types of wind tunnels and several different ways to classify wind tunnels. On the basis of Speed Regime developed in the test section relative to the speed of sound (Mach Number 'M'), Wind Tunnels are classified as subsonic ($M < 0.8$), transonic ($0.8 < M < 1.2$), supersonic ($1.2 < M < 5.0$), hypersonic ($M > 5.0$). On the basis of Tunnel Geometry, Wind tunnels are classified as Closed Circuit Wind tunnel (CCWT) and Open Circuit Wind Tunnel (OCWT) (Fig. 1). A wind tunnel that is closed and re-circulates the air through the test section is called a Closed Circuit Wind Tunnel. A wind tunnel that is open on both ends and draws air from the atmosphere into the test section is called an Open Circuit Wind Tunnel [5, 6].

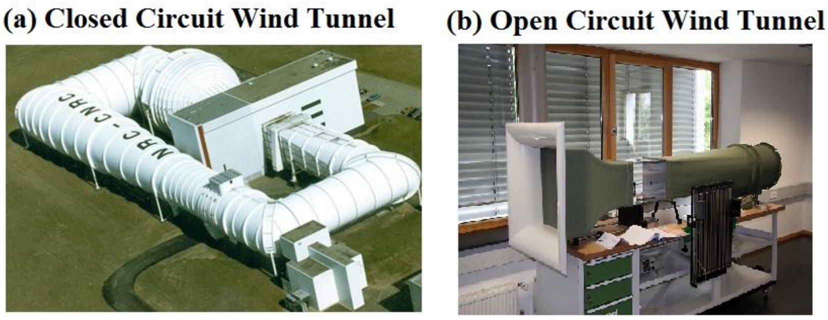

Fig. 1: Classification of Wind Tunnels on the basis of Tunnel Geometry as (a) Closed Circuit Wind Tunnel and (b) Open Circuit Wind

The OCWTs Models are used to investigate the different automotive designs by testing on scale models of cars, trucks etc. Airflow over a vehicle determines the drag forces, which in turn affects the vehicle's performance and efficiency. The three basic forces are lift, drag, and side force as measured in an axis system referenced to the direction of the vehicle. The concept of Lift and Drag can be understood with the help of airfoil. The airfoil long in the direction perpendicular to the plane of the drawing and the flow can be considered as two dimensional. The airfoil is tilted with respect to the (undisturbed) flow direction, defined by the angle of attack (AOA). The force experienced by airfoil is F_R. Decomposing the force F_R into components F_L and F_D {Given by (1) and (2)} perpendicular and parallel to the flow direction. F_L is termed as lift force and F_D is termed as drag force, the resistance to be balanced by the propulsion force generated by the engines (Fig. 2). The expressions for Lift and Drag Forces are as follows:

$F_L= 0.5\ C_L\ \rho\ A_1\ u^2$ ….(1)

$F_D= 0.5\ C_D\ \rho\ A_2\ u^2$ ….(2)

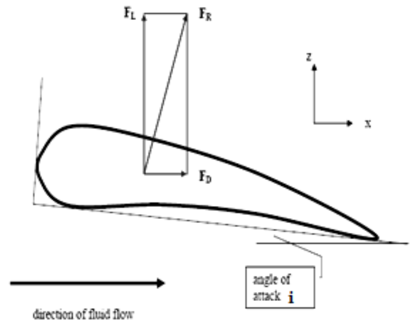

Fig. 2: Lift and Drag Forces on Airfoil subjected to fluid flow

The designer of an airplane tries to maximize C_L and to minimize C_D. C_L and C_D are dependent on the angle of attack. Usually the C_L drops sharply and C_D increases strongly at $i = 15^{\circ}$ (approx.) [7].

Wind tunnels have been used widely to simulate airflow about complete aircraft, specific aircraft components, and to conduct fundamental research concerning flow phenomena related to flight for over a century. Wind tunnels are made in different shapes and sizes, from just 30 cm long to large enough to contain a passenger airplane. The various sorts of Wind Tunnels find potential applications in estimation of pollution dispersion level near the building, investigation of wind-driven rain and building envelop, various aspects of wind loading on roofs and wind effects on towers and bridges. In Wind Engineering, wind tunnel tests are used to measure the velocity around, and forces or pressures upon structures. Very tall buildings, buildings with unusual or complicated shapes (such as a tall building with a parabolic or a hyperbolic shape), cable suspension bridges or cable stayed bridges are analyzed in specialized atmospheric boundary layer wind tunnels. The basic idea behind all wind tunnels is universal. Depending upon the situations like thermal and hydraulic testing, it generates uniform air flows with low turbulence intensity. The aerodynamic principles of the wind tunnel work equally on watercraft, except the water is more viscous and so sets greater forces on the object being tested. External flow tunnels are used to study the external flow through the chassis climatic tunnels and used to evaluate the performance of door systems, braking systems etc. under various climatic conditions. Aero-acoustic tunnels are used in the studies of noise generated by flow and its suppression. Wind tunnel tests are also performed to measuring the air movement of the fans, Turbine Blades, Propellers etc at a specific pressure exactly [3, 8-12].

A lot of research work have been accomplished to optimize the Wind Tunnel Design and still to make it better at various levels depending upon the situations research work is still in progress. Peter et al. in their work, focused on the wind tunnel test section flow quality and its application to a numerical CCWT by studying the effects of various variables for its evaluation [8]. Diana et al. evaluated the design criteria that supported the choice of the original solution for potential application of a new large wind tunnel in Civil, Environmental and Aeronautical aspects and discussed the feasibility of a plant on the basis of experimental analysis on a 1:9 scale model [13]. Lohan [14] focused on the design and application of LSWTs having well-defined, controllable, uniform flow of air for experimental and design validation purposes. Senol and Cinar with the help of Flow Simulation Fluent 6.0 program corrected the earlier developed design of a suction-type SOWT by simulating it in computer environment [15]. Eckert et al. discussed some Aerodynamic design guidelines and computer program for estimation of SSWT performance [16]. The enormous amount of research work and experiments undertaken in wind tunnels and their importance for human life motivated the high demands that are posed on optimum design level for Wind Tunnels against the minimum cost with optimum output. This paper deals with the Sub-Sonic Open Circuit Wind Tunnel (SOWT) with negligible effect of compressibility. Following the research works and significant guidelines related to design consideration, the design for SOWT Model is developed. The Mach Number of 0.15 allows it to use for aerodynamics tests and performance of some scale models having speeds around 150 km/hr.

II. Design of Sub Sonic Open Circuit Wind Tunnel Model

The Wind tunnels cannot be perfect simulations of environmental conditions, but up to some extent they can be treated as ideal to surrounding conditions. The degree to which they are flawed is measured with the help of Reynolds Number. The SSWTs are designed to provide a well-defined, controllable, uniform flow of air for experimental and design validation purposes. These tunnels when applied as open circuit cannot be used where a very high accuracy level and precise results are required due to their inability to control air flow up to a large extent. However, with proper designs and controlled instrumentation, these tunnels can be made to produce accurate results within close limit to practical value. The major advantage associated with this tunnel is its Set-Up and Maintenance Cost, which is very small as compared to CCWT. The leading manufacturer of automobiles use the OCWTs for the Drag and performance estimation of the vehicles as with current technology & designs, these tunnels are giving results quite close to practical values under proper calibrations.

The OCWT (Fig. 3) consists of five basic parts, which are (From front to back) the Settling Chamber, the Contraction Cone, the Test Section, the Diffuser and the Drive Section. The Settling Chamber is at the very front of the wind tunnel and is made up of screens and honeycomb-shaped mesh, which straighten out the air and reduce turbulence. The Contraction Cone forces a large volume of air through a small opening in order to increase the wind velocity in the tunnel, as there is gradual decrease in area. The Test Section is the place where a model is mounted on sensors. The Diffuser is at the end of the Test Section and keeps the air running smoothly as it goes toward the back. It also increases in volume in order to slow the air down as it exits the tunnel. The Drive Section is at the very back of the wind tunnel, and it is where the fan is housed and draws air into the wind tunnel by blowing air out of it and hence reduces turbulence along with greater control of the airflow through the tunnel. The decisive characteristic of wind tunnels lies in the flow quality inside the test chamber and the overall performances.

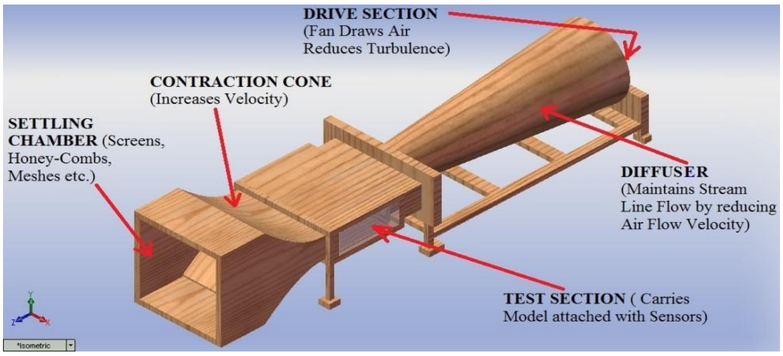

Fig. 3: Isometric View of Sub-Sonic Open Circuit Wind Tunnel Model developed Solid-Works

Three main criteria that are commonly used to define them are: maximum achievable speed, flow uniformity and turbulence level. Hence in general, the design aim of a wind tunnel is to get a controlled flow in the test chamber, achieving the necessary flow performance and quality parameters. The main specifications for a wind tunnel are the dimensions of the test section and the desired maximum operating speed. Also, it is crucial to avoid flow separation close to the walls of the contraction zone. In the subsequent sections, the design of each of the component of the Wind Tunnel is developed one by one, from the design of the Test Chamber to the Diffuser.

2.1 Test Chamber Design

The test chamber (Fig. 4) is the most delicate part of the tunnel and is also called as “The Heart of the Wind Tunnel” as it is the region for experimental study, carrying the scale model, sensors etc along with the controlled flow. Its size must be defined according to the wind tunnel main specifications, which also include the operating speed and desired flow quality. Its size and operating speed determine the maximum size of the models and the maximum achievable Reynolds number. In most of the cases, its cross-section is square in shape and its area should be decided according to the scale model which is going to be tested. The equivalent frontal area of the model should not be higher than 10% of the test chamber cross-sectional area. The width to height ratio adopted for 3-D Tests is 4:3. The Test Section Assembly is composed of the Test Section (Plexiglas) to avoid pressure loss and the Test Section Base (wooden stand and sensor mounts) [14-19].

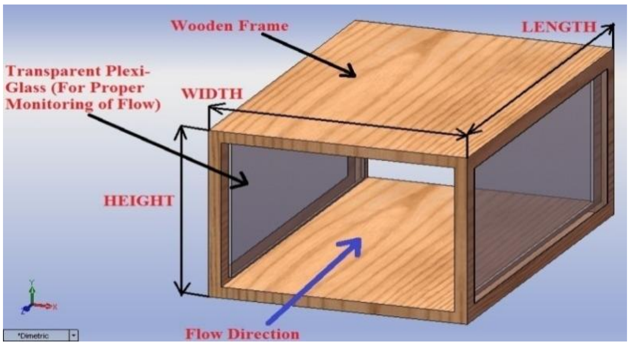

Fig. 4: Dimetric View of The Test Chamber developed using Solid-Works.

2.2 Contraction Cone Design

The Contraction Cone is the most important part in the design of a Wind Tunnel as it has the highest impact on the Test Chamber flow quality. It accelerates the flow from the Settling Chamber to the Test Chamber as such also known as ‘Nozzle’. It also helps in reduction of flow turbulence and non-uniformities in the test chamber. The flow acceleration and non-uniformity attenuations mainly depend on the ratio of cross-section area of inlet to that of exit, termed as contraction ratio (**N**). Theoretically, the value of N should be as large as possible but it has an upper limit as it strongly influences the overall wind tunnel dimensions and hence its cost. For the Wind Tunnels used in civil or industrial applications, a contractions ratio between 4.0 and 6.0 may be sufficient reducing the flow turbulence and non-uniformities levels to the order of 2.0%, which is acceptable for many applications. Further with just one screen placed in the settling chamber it reduces to 0.5%. Even this is a very reasonable value for some aeronautical purposes.

$$\textbf{N (Contraction Ratio)} = \frac{\text{Area at entry of C.C.}}{\text{Area at exit of C.C.}} \quad \text{....(3)}$$

The second characteristic of the contraction Cone is its shape, taking into account that the contraction is rather smooth. For this 1-D (One-Dimensional) approach to the flow analysis is applied to determine the pressure gradient along it. The important point of consideration is the pressure distribution on the contraction walls, as if it has some regions with adverse pressure gradient, it may produce local boundary layer separation which can increase the turbulence level considerably, resulting in poor flow quality in the test chamber. The solution to this is to make the ratio of the radius of curvature to the flow width about the same at each end. But at the upstream end the radius of curvature cannot be too large as it leads to slow acceleration and therefore increased rate of growth of boundary-layer thickness which causes centrifugal instability in the tunnels having laminar flow. The contraction semi-angles: $\alpha/2$ and $\beta/2$ are taken to be in the order of 12º, this causes the contraction cone to possess a reasonable length and a good fluid dynamic behavior. Bradshaw et al. recommended two segments of third degree polynomial curves for deciding the exact curve (Fig. 5) for the Contraction Cone [14-20]. The polynomials are:

$y = a_W + b_W x + c_W x^2 + d_W x^3$ ....(4)

$y = a_N + b_N x + c_N x^2 + d_N x^3$ ....(5)

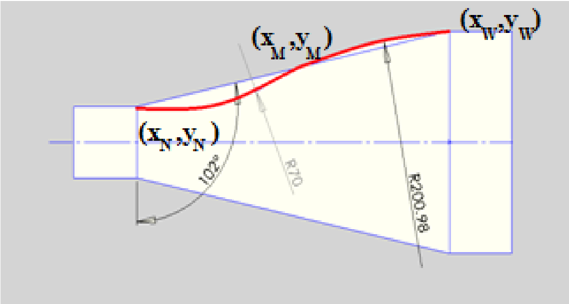

Fig. 5: Fitting Polynomial for the Contraction Cone Curve developed using Solid-Works

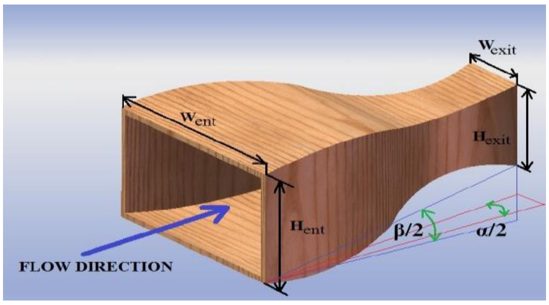

Fig. 6: Isometric View of The Contraction Cone developed using Solid-Works

The Contraction Cone developed using the above curve (Fig. 6) doesn't allow boundary layer to separate and keep boundary layer thickness within certain limit. It provides the favorable flow to the Test Chamber.

2.3 Settling Chamber Design

The Settling Chamber (Fig. 7) is the very first region designed to provide controlled high quality flow to the Contraction Cone by attenuating the various flow components responsible for turbulence. To develop high quality flow some devices like screens and honeycombs etc are installed to increase the flow uniformity and to reduce the turbulence level at the entrance of the contraction cone. They produce a relatively high total pressure loss. Honeycomb is very efficient at reducing the lateral turbulence, as the flow pass through long and narrow pipes. But the problem with Honeycombs is, it introduces axial turbulence of the size equal to its diameter which restrains the thickness of the honeycomb. To tackle this problem, Screens are introduced as they reduce longitudinal turbulence very efficiently. In this case, the problem is that in the Contraction Cone the lateral turbulence is less attenuated than the longitudinal one. Hence, to obtain better flow characteristics, a combination of Honeycombs and Screens is used. This configuration requires the honeycomb to be located upstream of 1 or 2 screens [14-21].

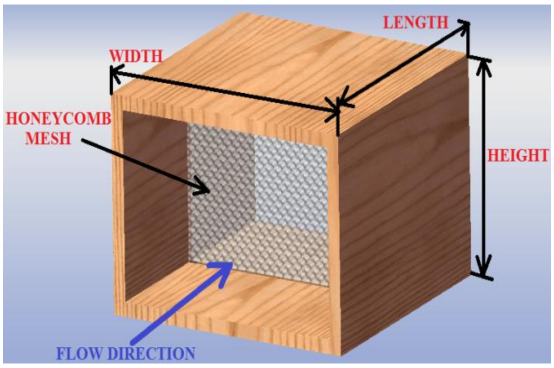

Fig. 7: Isometric View of The Settling Chamber developed using Solid-Works

2.4 Diffuser Design

The Diffuser (Fig. 8) plays an important role in controlling the flow quality inside the Test Chamber by avoiding the flow detachment as in case of flow detachment; the pressure pulsation is transmitted upstream into the test chamber, resulting in pressure and velocity non-uniformities. To avoid flow detachment, the maximum semi-opening angle in the diffuser has to be smaller than 3.5° [14-21].

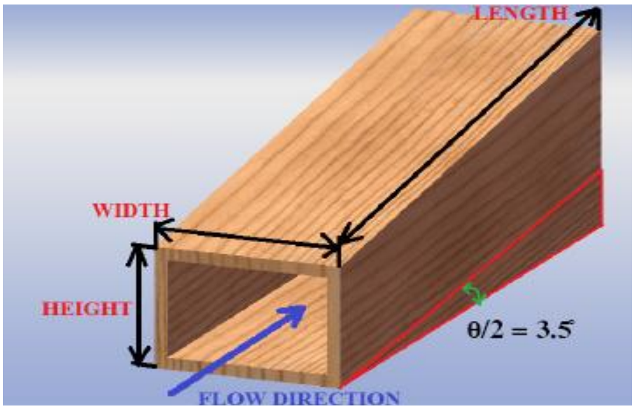

Fig. 8. Dimetric View of The Diffuser developed using Solid-Works.

III. Analysis of Sub Sonic Open Circuit Wind Tunnel Model

The Primary Design Parameters for the overall design of the Wind Tunnel include Test chamber dimensions i.e. Width (W_T), Height (H_T) and length (L_T). With the help of these parameters cross-sectional area of the Test Chamber can be calculated as $A_T = W_T.H_T$. The hydraulic diameter is given by the relation [14-21]:

$$D_T = \frac{2\,W_T\,H_T}{(W_T + H_T)} \quad ....(6)$$

The Contraction ratio (N) is taken 5 for the Wind Tunnel with Mach number (M=0.15), having Maximum operating speed (V_T) to be 50 m/s. These Design variables can be summarized in the Table. 1. The dimensions for the Test Section are W_T = 24cm, H_T = 18cm, L_T = 45cm and the V_T is taken to be 50m/s which gives us the Mach Number (M) to be 0.15. So, The Designing of all other parts is done based on these dimensions with N = 5. The semi angle in the Contraction Cone (α/2) is taken as 12° and the semi angle in the Diffuser (θ/2) is taken as 3.5° . The non dimensional lengths for the Settling Chamber (l_S) and Diffuser (l_D), for Sub-Sonic Open Circuit Flow, are taken as 0.5 and 3.2 respectively. The calculated parameters are displayed in Table. 2. And the final design for this analytical analysis is represented by (Fig. 9). The total length of the SOWT is:

$$\mathbf{L_{WT} = L_S + L_C + L_T + L_D \quad ....(7)}$$

$$\mathbf{L_{WT} = 26.83 + 45 + 69.78 + 76.80 = 218cm}$$

Hence, $\mathbf{L_{WT}}$ is equal to **218cm.**

Table. 1: The primary and secondary design parameters required for designing of SOWT Model

PRIMARY DESIGN PARAMETERS	SECONDARY DESIGN PARAMETERS
Test Chamber Width (W_T)	Semi Angle In Contraction Cone (α/2)
Test Chamber Height (H_T)	Semi Angle in Diffuser (Θ/2)
Test Chamber Length (H_T)	Settling Chamber Non Dimensional Length (L_S)
Contraction Ratio (N)	Diffuser Non Dimensional Length (L_D)
Maximum Operating Speed (V_T)	Settling Chamber Length (L_S)
Mach Number (M)	Contraction Cone Length (L_C)
	Diffuser Length (L_D)

Table. 2: Secondary design Parameters of SOWT Model

Secondary Parameters	Expressions	Values
Cross-Sectional Area of the Test Chamber (A_T)	$A_T = W_T H_T$	432 cm^2
Hydraulic Diameter of the Test Chamber (D_T)	$D_T = \frac{2W_T H_T}{W_T + H_T}$	20.57 cm
Length of The Contraction Cone (L_C)	$L_C = \frac{(\sqrt{N} - 1) W_T}{2\tan(\alpha/2)}$	69.78 cm
Length of The Settling Chamber (L_S)	$L_S = \sqrt{N} W_T l_S$	26.83 cm
Length of The Diffuser (L_D)	$L_D = W_T l_D$	76.80 cm

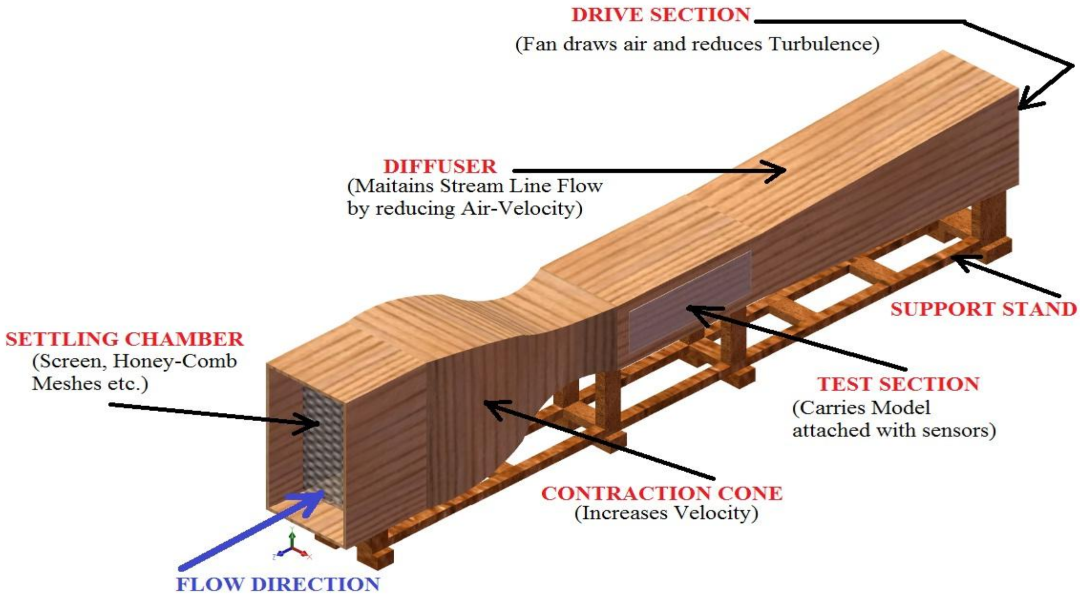

Fig. 9: Isometric View of the complete model of SOWT developed using Solid-Works

IV. Instrumentation of Sub Sonic Open Circuit Wind Tunnel Model

The instrumentation of wind tunnel emphasizes on the various instruments and Data Acquisition Systems (DAQs) required by a tunnel for its proper functioning, Pressure and Flow measuring ability, Flow Visualization and Image Acquisition. In the instrumentation of the tunnel, Standard data acquisition (DAQ), Motion Control, and Image Capture hardware play a very crucial role. Data acquisition is the process of sampling signals that measure real world physical conditions and converting the resulting samples into digital numeric values that can be manipulated by a computer. Data acquisition systems convert analog waveforms into digital values for processing. The various components of data acquisition systems are Sensors (convert physical parameters to electrical signals), Signal conditioning circuitry (convert sensor signals into a form that can be converted to digital values) and Analog-to-Digital converters (convert conditioned sensor signals to digital values). Further, various operations can be integrated to the system including Flow Visualization with Image Acquisition, Multipoint differential pressure scanning, Hot Wire Anemometry, Force and Moment measurement using internal balances, Roll, Pitch and Yaw angle measurements, and Noise and Temperature measurements.

For Pressure and Flow Measurements, measuring devices coupled with DAQs like LabVIEW and pressure scanners etc. can be used. Similarly for Force and Moment Measurements, Six-component Strain Gauge Balances can be applied. And for Flow Visualization and Image Acquisition, light sheets using Argon-ion lasers with CCD cameras and recording system can be used to capture and analyze the exact trajectory of flow particles, even sometimes incorporating IMAQ hardware and software (IMAQ vision). With such a proper design and proper instrumentation, a wind tunnel can be used for Full-model tests with sting support mechanism, Half-model testing with external balance, Two-dimensional model testing, Ground effect simulation with moving belt, Gust and cross wind simulation, Aero-acoustic testing etc. For a Wind Tunnel with $M < 0.3$, the instrumentation required is not so much complex but still it requires attention for getting accurate and precise results [22-26].

V. Simulation of Sub Sonic Open Circuit Wind Tunnel Model

Solid-Works Flow-Express is a first pass qualitative flow analysis tool which gives insight into water or air flow inside the Solid-Works model. Using this, the simulation is carried out. The constants and assumptions used in the simulation study are tabulated as (Table. 3):

Table. 3: The constants and various parameters determining the environment conditions for the simulation of SOWT Model.

CONSTANTS AND VARIOUS PARAMETERS	VALUES
Inlet Pressure	100890 Pa
Outlet Pressure	100000 Pa
External Ambient Temperature	293.20° K
Gas Constant	287 J/kg-° K
Kinematic Viscosity	1.714×10^{-5} Kg/m-s
Acceleration due to gravity	9.81 m/s^{-2}
Air Density	1.2251 kg/m^3
Entrance Speed	11.335 m/s

The flow velocity simulation of the designed Wind Tunnel have been performed (using particle flow visualization) under the above mentioned environment conditions (Fig. 10). Also, the variation of flow velocity against the length of the tunnel is obtained. Fig. 11 shows the flow speed changes within the wind tunnel. The lowest flow speed is occurred at the surfaces of the entrance section, at the corners joining the settling chamber and the contraction cone, and the diffuser exit. Flow speed accelerates while passing through the contraction and it reaches the highest required value (49.118 m/s ≈ 50 m/s) in the test chamber. Also the flow rate increases throughout the contraction and remains constant throughout the test chamber. Flow rate gradually decreases as air exits from the test chamber and enters into the diffuser. Further, at the diffuser exit, it reaches the same value with the wind tunnel entrance.

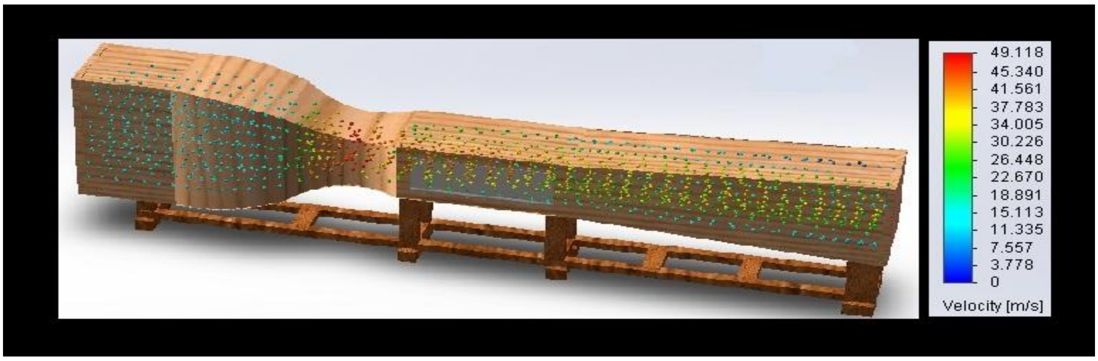

Fig. 10: Particle Flow Visualization of Air as fluid inside the SOWT, illustrating Velocity variation along the length of the Tunnel

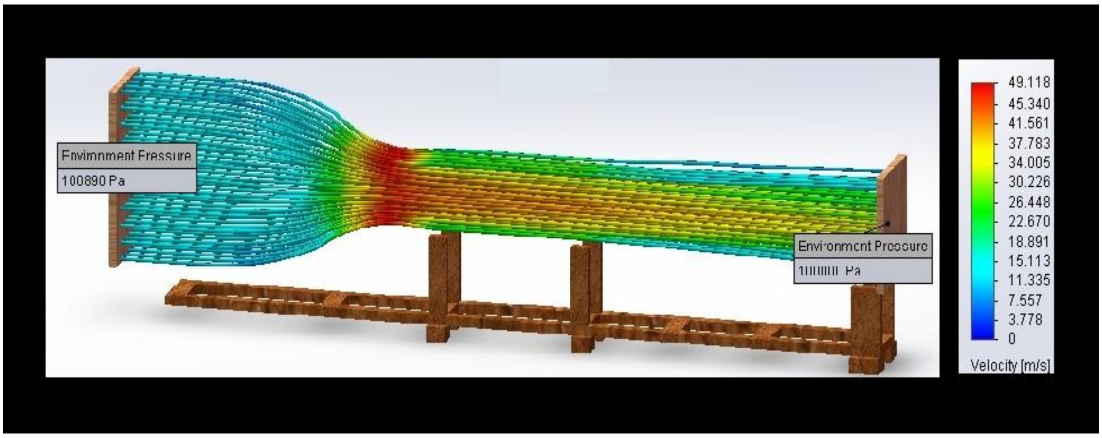

Fig. 11: Flow Velocity Variation of Air as fluid inside the SOWT along the length of the Tunnel

The graphic of static pressure distribution and velocity changes throughout the wind tunnel is shown in Fig. 12. The static pressure on the edges of the entrance section is the maximum value (100890 Pa.). It can be said that a major turbulence and counter pressure zone are created at these points. Static pressure values are closed to the each others at the settling chamber (x=2.5 ft.) and the diffuser exit (x=7 ft.). A bit of static pressure drop is occurred in the middle zone of the contraction cone. The pressure is reached to the lowest value at the test chamber exit. Since the static pressure changes are very small throughout the test chamber, it can be said that there is not any boundary layer thickening along the test chamber walls and the air flow quality is good.

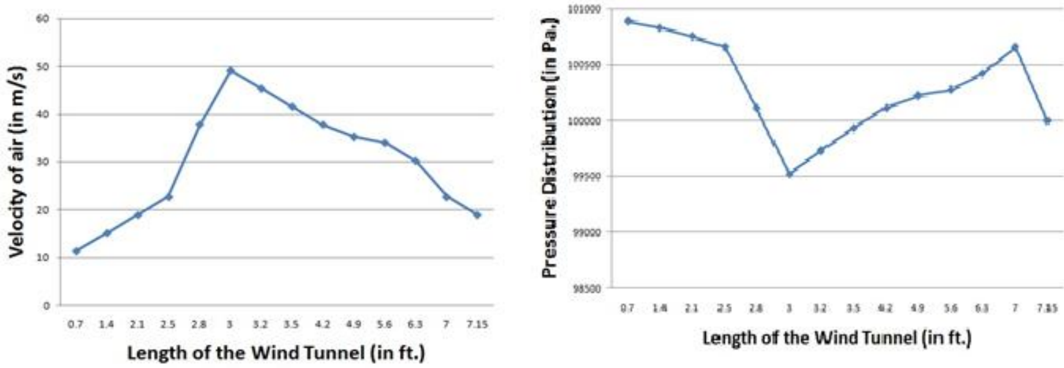

Fig. 12: Flow Velocity Variation (Quantitatively) and Pressure Distribution (Quantitatively) of Air as fluid inside the SOWT along the length of the Tunnel

VI. Conclusion

The design of Low Cost SOWT model has been generated. The main considerations like Boundary Layer Separation, Controlled Air Flow Quality, Turbulence Intensity, Stream Line Flow, Cost-Effectiveness, Design Ease and Mach Number (M = 0.15) etc were taken into the account and accordingly the model is designed. The primary design parameters of the Test Chamber were taken as the baseline and following the design guidelines, the secondary design parameters for approximately 220 cm tunnel were calculated. The Contraction Cone and the Test Chamber section were given special attention as they have direct influence on the scale model testing and the data generated. A brief insight is given to the instrumentation segment of the tunnel, especially to the various measurements and DAQs that are still playing their part in research and development concerning the various wind tunnel applications. The Velocity Variations and Static Pressure changes throughout this model were simulated. Moreover, the quantitative variation of Velocity and Pressure is plotted against the tunnel's length. With the final design, the maximum operating speed obtained at the test chamber is 49.12 m/s, quite close to desired value 50 m/s. The air flow obtained is of smooth quality with no boundary layer thickening process at the Test Chamber. Thus, the final SOWT Model design obtained can be used wherever the maximum operating velocity required is 50 m/s or 180 km/h, which generally is the case with the automobiles at high speeds.

References

[1]. Dodson, MG (2005), An Historical and Applied Aerodynamic Study of the Wright Brothers, Wind Tunnel Test Program and Application to Successful Manned Flight, US Naval Academy Technical Report, USNA-334.
[2]. Whirling Arms and the First Wind Tunnels, Wind Tunnels of NASA by Donald D. Baals and William R. Corliss, (Searched on Sept 1, 2013) http://www.grc.nasa.gov/WWW/k12/WindTunnel/history.html.
[3]. History, Origins of Wind Tunnel, NASA Aeronautics and Space Administration, http://en.wikipedia.org/wiki/Wind_tunnel (Searched on Sept 1, 2013).
[4]. Wright Brothers, National Memorial, Wind Tunnel Tests 1901, (Searched on Sept 1, 2013) http://www.cr.nps.gov/history/online_books/hh/34/hh34i.htm.
[5]. Types of Wind Tunnels, NASA Aeronautics and Space Administration, (Searched on Sept 1, 2013) http://www.grc.nasa.gov/WWW/k12/airplane/tuntype.html.
[6]. Science Buddies: How to Build a Subsonic Wind Tunnel (Searched on Sept 1, 2013) http://www.sciencebuddies.org/science-fair-projects/wind-tunnel-toc.shtml.
[7]. A Textbook of Fluid Mechanics and Hydraulic Machines, Dr. R. K. Bansal, Laxmi Publications Pvt. Ltd., New Delhi, Forces on Submerged Bodies, Page No. 657-659.
[8]. Peter Moonen, Bert Blocken, Jan Carmelieta, Indicators for the evaluation of wind tunnel test section flow quality and application to a numerical closed-circuit wind tunnel, Journal of Wind Engineering and Industrial Aerodynamics 95 (2007) 1289–1314.
[9]. Aly Mousaad, Alberto Zasso and Ferruccio Resta (2011), On the dynamics of a very slender building under winds: reponse reduction using MR dampers with lever mechanism, The Structural Design of Tall and Special Buildings.
[10]. Windless Wind Tunnels for High Altitude Tests, Popular Mechanics, February 1952, Page No-105.
[11]. J.E. Cermak, Wind tunnel for the study of turbulence in the atmospheric surface layer, Final Report Air Force Cambridge Center, Air Research and Development Command, Bedford, MA (Contract AF 19(604)-1706), 1958, 36 pages.
[12]. R.E. Whitbread, The measurement of non-steady wind forces on small-scale building models, in: Proceedings of the fourth International Conference on Wind Effects on Buildings and Structures, Heathrow, England, 1975, pages-567–574.
[13]. G. Diana, S. De Ponte, M. Falco, A. Zasso, A new large wind tunnel for civil-environmental and aeronautical applications, Journal of Wind Engineering and Industrial Aerodynamics 74-76 (1998) 553-565.
[14]. John Lohan, PhD, Article on Design and Applications of Low Speed Wind Tunnels, Department of Mechanical and Industrial Engineering, Galway-Mayo Institute of Technology (GMIT), Dublin Road, Galway, Ireland.
[15]. Serhat Senol, Ali Cinar, Design and Flow Simulation of an Open Circuit Wind Tunnel, EnginSoft International Conference 2009 1st-2nd Oct. 2009.
[16]. Eckert W. T, Mort K. W, & Jope J, Aerodynamic design guidelines and computer program for estimation of subsonic wind tunnel performance, NASA technical note / D-8243, NASA Washington, (1976).
[17]. Maskell, E. C. A theory of the blockage effects on bluff bodies and stalled wings in a closed wind tunnel, R. & M. 3400, November, (1963).
[18]. The Royal Aeronautical Society. Wind tunnels and wind tunnel test techniques, Royal Aeronautical Society London, (1992).
[19]. Mehta, R. D, & Bradshaw, P. Design Rules for Small Low-Speed Wind Tunnels, Aero. Journal, (Royal Aeronautical Society) , (1979), 73, 443.
[20]. Borger G. G., The optimization of wind tunnel contractions for the subsonic range, NASA Technical Translation / F-16899, NASA Washington, (1976).
[21]. Scheiman, J. Considerations for the installation of honeycomb and screens to reduce wind-tunnel turbulence, NASA Technical Memorandum / 81868, NASA Washington, (1981).
[22]. Gorlin, S. M, & Slezinger, I. I. Wind tunnels and their instrumentation, Israel Program for Scientific Translations Jerusalem, (1966).
[23]. Data Acquisition, (Searched on Sept 15, 2013) http://en.wikipedia.org/wiki/Data_acquisition.
[24]. Kamal Poddar, Sanjay Gupta, Instrumentation for National Wind Tunnel Facility, IIT Kanpur.
[25]. Barlow, J. B, Rae, W. H, & Pope, A. Low-speed wind tunnel testing, John Wiley & Sons New York, (1999).
[26]. Sub-Sonic Wind Tunnels and Instrumentation, www.aerolab.com, 301-776-6585 Laurel, Maryland, USA.