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THE MAIN DESIGNS CRITERIA FOR A LOW SPEED SUBSONIC WIND TUNNEL

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Abstract: *This work describes the designs criteria and construction details of the four main parts of a medium size subsonic low speed wind tunnel (test section, drive system, blade design and contraction section). This wind tunnel was designed to achieve 90 m/s in the working section with low intensity turbulence level (0.2%) making it available for research in areas such as low speed aerodynamics (flight and terrestrial vehicles), sport activities, civil engineering applications, fundamental research in Fluid Mechanics and other possibilities. In order to accomplish such objectives a very detailed design was carried on through the use of CFD analyzes and theoretical and semi-empirical methods in order to improve the flow quality inside the wind tunnel sections. A very careful attention has been focused to the design of the fan blades and the electrical engine assembly. The design and construction of the drive system, fan blades , test section and contraction section has been presented and discussed shedding light to the most relevant technical aspects and an attempt is made here to present some design and manufacture guidance for the main components of a low subsonic wind tunnel.*

Keywords*: wind- tunnel, low , aerodynamics, design, CFD*

1. INTRODUCTION

A wind tunnel is an essential tool for engineers since the practice of low-speed experimental aerodynamics has continued to evolve and continues to be a cornerstone in the development for a wide range of vehicles and other devices. It was believed that in the 1970s and in the early 1980s that the use of wind tunnels, especially in the subsonic regime, would rapidly disappear as computational fluid dynamics (CFD) would become a more attractive option to obtain data for a wide range of engineering applications. A well designed wind tunnel could supply technical information for a large number of engineering applications such as external aerodynamics (flow over terrestrial and aerial vehicles), civil engineering (flow over bridges, buildings, cables, etc.), sport activities (flow over cyclists, design of volley and basket balls, wind sails, etc.), fundamental fluid dynamics (laminar and turbulent flow over simple and complex geometries) and an extensive frame of other options in industry.

Although there are two basic types of wind tunnels, the open circuit and closed circuit, this paper concentrates on the design only of the second type, as seen on Fig(1). The most high performance wind tunnels were designed as closed-circuit to ensure a controlled return flow through the use of corner turning vanes and screens. Other advantages of closed circuit tunnels are the independence of other activities in the building and weather conditions; less energy required for a given test-section size and velocity; another significant advantage is less environmental noise when operating. The disadvantages are the higher initial costs, due to return ducts and corner turning vanes; if smoke is extensively used for flow visualization or running of internal combustion engines, it is necessary to purge the tunnel and some method of cooling for high utilization of the tunnel.

There are several references for wind tunnel design in open literature. The following main references have been consulted for designing a low speed wind tunnel: Muncey & Pote (1956), Mehta & Bradshaw (1979), Barlow, Rae & Pope (1999), Cattafesta et al.(2010), Bell & Mehta (1989), Bell & Mehta (1988), Lindgren & Johansson (2002), among others. The tunnel requirements used as reference in this work, as shown in the beginning, are: low-speed (subsonic at Mach 0.26) wind tunnel for research and educational purposes, closed-circuit with flow passive control (corner-vanes and stabilization chamber). The design criteria has been set to enable measurements of accurate steady or unsteady data with low turbulence intensity in order to facilitate study of the physical phenomena of interest. Moreover, it could be further improved for boundary-layer transitions experiments and aeroacoustics analysis.

Based on these requirements, the main characteristics were defined as shown in the sequence. The closed-circuit wind tunnel counts with approximately 30 meters length and 10 meters width. The wind tunnel material is a treated naval-wood panels for covering the side of sections. Requirements for surface treatment have been placed with polishing at surfaces and covering any screw and/or slot present in each section. The whole structure (skeleton) was made by metal rods – fuselage type construction. The maximum air speed at test chamber is to reach 90 m/s with a prescribed turbulence level of 0,2% and minimum flow velocity: 5 m/s. Test chamber dimensions: 1,7 m x 1,2 m (2.04 m^2), with 3.0 m length. Acrylic access doors with interchangeable panels are placed in the test section. A stabilization chamber with screens and honeycombs for flow control has been included. A Contraction ratio between of 12:1 in order to reach speed requirements was designed. The Drive System consists on a Triphase 8 poles, 380 V e 350 hp engine equipped with an air cooling system, and fairing integrated in order to reduce flow disturbance and heating. The system also counts with an engine speed control operating through frequency inverter. The Fan Blades are 8 blades of composite material, with approximately 3 m diameter and adjustable pitch for reaching optimum operational condition. The drive system is structural isolated from other sections of the tunnel, in order to avoid vibration.

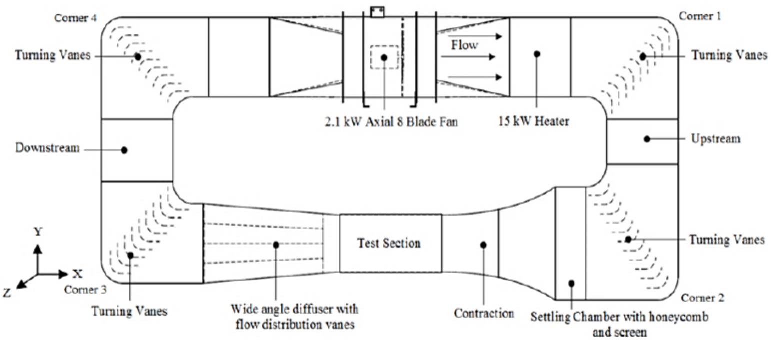

Figure 1: Closed-circuit wind tunnel designs – after Chaudhry et al (2015).

Four aspects of the wind tunnel design are described in the following sections and compared to the available data in literature.

1.1. Test section

Over the years, many shapes have been used for test sections, but it was proven that the cost and power are directly determined by the cross-sectional area and the length, being the difference in losses in the test section due to the cross-sectional shape negligible. Aware of this, the shape of the test section should be based on the utility and considerations of the aerodynamics of the models to be tested. Another factor that requires attention is the fact that as the air proceeds along the test section, the boundary layer thickens. This action reduces the effective area of the jet from that of geometric and causes an increase in the flow speed outside the wall boundary layers. The length of the test section in tunnels designed with aeronautical work as the primary focus varies from one to two times the major dimension of the section. Another important detail in the test-section design is the installation of sufficient windows for viewing the model, those windows should be made of shatter resistant material for safety reasons. Adequate lighting is also needed; both to work on the model and for photographic purposes, some tunnels have lights built into them, in order to facilitate the experiments visualization (Jewel. et al., 1999).

Taking into account all the listed items above, a test section with dimensions 1,70 m x 1,20 m x 3,0 m was constructed to meet the requirements; including a large access door made of acrylic for making easy the application of visualization techniques such as smoke's rake or PIV (Particle Image Velocimetry). It is important to emphasize that the other lateral panels could be replaced at any time with acrylic panels and/or other specific material such as wood. The test section illumination is completed with LED lamps over the floor and ceiling throughout the length of the test section. At the floor there is the aerodynamic balance access platform, which is a circular disk of dimension 1 m – as seen in Fig. (9). A common rule of thumb has been set in accordance with the Bradshaw and Meta (2003), were the test section rectangular dimension sizing is around 1.4 : 1.

1.2. Drive system

The most common device for driving the flow in subsonic wind tunnels is an axial flow fan or propeller. For closed-circuit tunnel, the usual configuration is a stator upstream of the rotor. This set is designed so that the swirl at exit is zero (Mehta and Bradshaw ,1979). The fan is the source of power input while the vanes are responsible for absorbing some energy in the process of carrying out their function. The fan and straighteners combined function is providing a rise in pressure as the flow passes through the section. The increase in pressure provided must be equal to the pressure losses throughout all other sections of the tunnel at any given steady flow operating condition (Jewel. et al., 1999).

The drive system will determine how the working fluid is moved through the test section, being its selection dependent on the medium and the operational regime. Barlow, Rae and Pope (1999) provide a procedure for estimating the losses incurred in the tunnel circuit, aiding in fan selection. In order to keep up with a flow velocity of 90 m/s at the test section the drive system proposed take into account an electrical engine with 350 hp equipped with an air cooling system. The axial fan efficiency is 0.90 and the global charge losses factor is 0.50. Since the test section area is 2.040 m², the described drive system will assure a mass flow of 170.311 kg/s, a volume flow of 151.522 m³/s and a dynamic pressure of 3,100.50 Pa. This engine is assembled with 8 fan blades with approximately 1 m long and fully streamlined with the flow through the use of fairings for covering the engine chassis. The air cooling system is forced by use of two additional small centrifugal blowers through ducts inside the main fairing. An important design choice for this component was the engine blade mounting which has been selected to be in a "pusher" configuration. In order to reduce the blade swirl ahead, a set of stator-vanes are mounted and rightly directed with the main flow, according to Fig. (2).

For the blades design, the Blade Element Theory (B.E.T) (Roskam, 1997 & Pawlowski, 1920) was applied with the following parameters considered: number of blades (8), motor speed (890 rpm), propeller diameter (2.2 m), spinner diameter (0.8 m), maximum operational speed at pumping chamber (48.3 m/s), maximum available power supplied by the electrical motor (260 KW); and atmospheric parameters: air density (ρ = 1.064 28kg/m³ @ 884 m, ISA + ΔT=16°C), kinematic viscosity (ν = 1.657 e -5 m^2/s) and speed of sound (a = 346.28 m/s) according to Fig. (2).

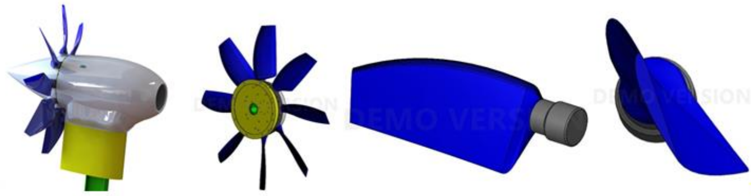

Figure 2: Engine assembly and blade design.

The whole drive system is completely segregated from the wind tunnel (i.e. there is no hard and/or physical connection between the engine and the wind tunnel structure) in order to avoid vibration in the structure and impact in the flow uniformity according to Fig. (3).

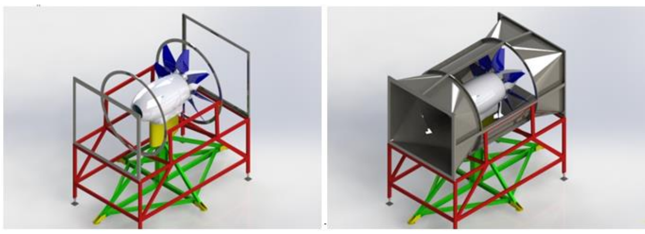

Figure 3: Description of the engine support and drive system chamber.

1.3. Contraction section

The contraction has a great importance in determining the flow quality in the test section. The contraction accelerates and aligns the flow into the test section (Derbunivich et al., 1987). The contraction stretches vortex filaments, which reduces axial but intensifies lateral turbulent fluctuations (Tennekes and Lumley, 1972). The length of the contraction should be sufficiently small to minimize boundary-layer growth and cost, but long enough to prevent large adverse pressure gradients along the wall, originated by streamline curvature, this phenomena can lead to flow separation. Morel (1975) suggested a simple analytical method of matched polynomials, according to the left side of Fig. (4). In the Fig. (4) the entrance height of the contraction is (Hi), and the exit height is (He). The total length of the contraction is (L), and the two polynomials are matched (location, slope, and curvature) at a specified location $x = x_m$. At the exit of the contraction, any remaining "free" higher-order derivatives of the polynomial are set to zero to obtain a straight section. Another way was recommended by Su (1992) which consists on matching a cubic polynomial at the contraction entrance with a higher-order polynomial at the contraction exit. Techniques using 3-D potential flow simulations inside the contraction followed by the application Stratford's (1958) separation criteria for turbulent boundary layers affected by adverse pressure gradients can be applied to develop optimized contractions meeting design criteria for test section flow uniformity (Mathew, 2005).

Aware of that, the designed contraction ratio achieved was 12:1 in order to meet the velocity requirements. According to Mehta & Bradshaw 1979, the design of a contraction is aimed to reach a uniform and steady stream at its outlet, and requires the avoidance of flow separation. Here, it has been selected a tradeoff between contraction length and contraction ratio. Since it has been invested in the inclusion of a settling chamber (including honeycombs and screens) it is expected that a higher contraction ratio could take place without jeopardizing the flow uniformity. Figure (12) shows details of the contraction. The contraction curve has been designed to reach a 1st and 2nd derivative at the inlet and outlet, according to the right side of Fig. (4).

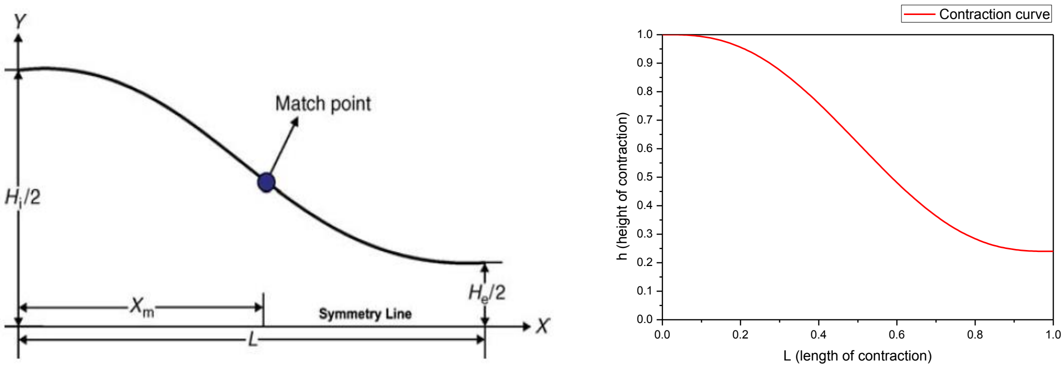

Figure 4: Schematic of the contraction shape with matched polynomials(left); Contraction Curve (right).

Also, the selected curve was applied to a tridimensional CFD model in order to verify the development of the boundary layer into the test section. The tridimensional CFD model was built in ANSYS 16.0® by considering a reduced size domain, including the contraction, the test section and the diffuser. In order to match the velocity speed at the test section some trials have been performed to adjust the boundary condition at the inlet of the domain. Fig. (5) illustrates the computational domain used in these simulations.

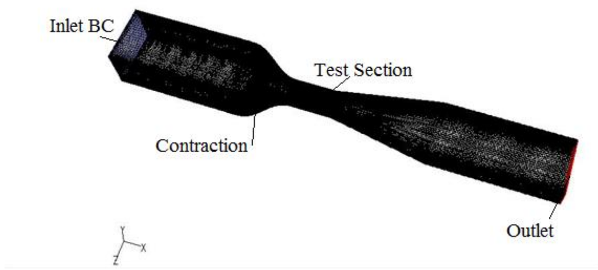

Figure 5: CFD computational domain.

The simulations were run for two different flow velocities in the test section: a) 12 m/s and b) 85 m/s. All simulations were performed with a standard k-ε turbulence model and the convergence criterion was met at 4 orders of drop magnitude. Some snapshots of the flow inside the contraction and in the test section are presented in Fig. (6).

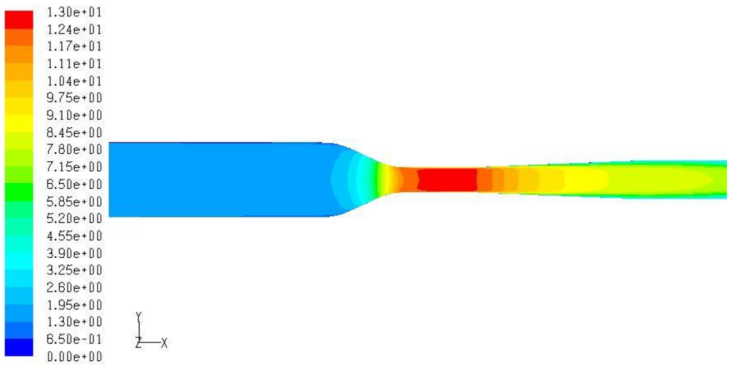

Figure 6: Contours of velocity magnitude.

Figure (7) represents the contours of velocity magnitude in a cross-sectional plane in the middle of the test section, were it is possible to see the development of the boundary layer. In order to estimate the boundary layer development this plot was taken over two positions, at the distances (L) of 1 m and at 3 m in the test sections. The values are given in the Tab. (1), where Ɛ represents the boundary layer.

Table 1: Boundary layer values obtained by CFD.

	L(m)	Ɛ (m)		L(m)	Ɛ (m)
V= 12 m/s	1.000	0.030	V= 85 m/s	1.000	0.020
	3.000	0.067		3.000	0.052

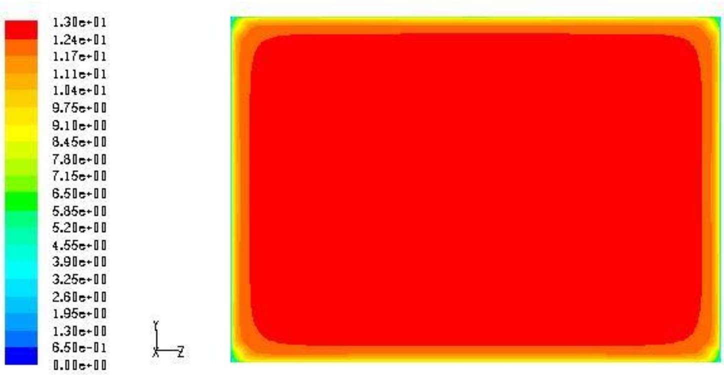

Figure 7: Contours of velocity magnitude in a cross-sectional plane in the test section.

These CFD data have been corroborated by the analytical solution of the Blasius equations. Figure (8) illustrates this comparison.

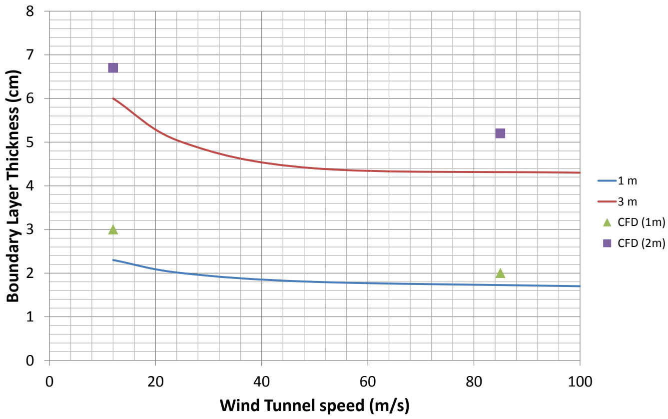

Figure 8: Comparison of boundary layer development (CFD vs Analytical solution).

2. WIND TUNNEL MAIN PARTS CONSTRUCTION

This section describes some details of the wind tunnel's construction. In this project, the wind tunnel construction was chosen to be similar to an aircraft fuselage, with main spars and ribs of steel covered by a skin of naval wood (treated for humidity and having a high level of surface finishing) – 18 mm MDF (Medium Density Fiberboard. The welding method was the MIG (Metal Inert Gas) with 2 mm width.

The test section was the second part to be built and a special attention was given to fix the MDF's panel on the main structure by using PVC (Polyvinyl Chloride) glue that has a rubber base. By making this procedure the vibration transferred to the wood panel was reduced, contributing to maintain the flow laminar. In addition, each wood panel was screwed in the spars and ribs throughout the whole section. Internally, each screw is covered with plastic resign in order to meet the surface finishing requirements. In order to avoid slots at the upper and lower corners (connection between the side wall panels) in all the connections it was used a composite based on PVC to seal the tunnel. As requirement, the test section has a polycarbonate door (transparent) hinged on three points and automatic actuated by an electric motor. An additional simple door will be placed at the end of the test section in order to make easy the access into this chamber every time is needed. Figure (9) shows the test section aligned with another part of the wind tunnel.

One of the most complex parts to build was the contraction. Since the contraction curves assume a prescribed curvature function, the fixing process of the MDF's panels took around 4 weeks to bend them without distortions. This was an extensive work (almost artisanal, developed by an experienced carpenter/woodworker). The contraction part is shown below in Fig. (10).

Figure 9: Test section (left); test section aligned with the smaller diffuser (right).

Figure 10: Contraction part - details.

The drive system consists of an electrical engine weighting around 2.000 kg and required especial attention to install it. It was built a segregated steel support for the motor in order to avoid vibration transmission to the tunnel, especially when starting the motor and at higher velocities of operation. The drive system section has stator vanes to remove swirl from the blades (8 blades of composite material turning at around 900 rpm) and to reduce the turbulence in the long diffuser. It was designed an aerodynamic fairing, as seen on Fig. (4), to the electrical engine which, together with the pusher configuration, achieves a better flow quality and helps to improve the engine cooling. Figure (11) shows the steel support and the motor installed on it, the drive system section, and the fairing (mold) for the electrical engine.

Figure 11: Engine support (left); drive system section (middle) and Cooling system to extract hot air inside the engine cavity (right).

In Fig. (11), it is also possible to see the engine intake that will get some amount of the main air flux to cool down the engine in order to keep the air temperature inside the wind tunnel constant during all operational velocities. This cooling system is coupled with the engine nacelle and removes the hot air inside the engine cavity due to the electrical dissipation over the engine chassis. The right side of Fig. (11) shows also an additional 4 hp electrical engine is used to suck the air and to through it to the environment.

The drive system also comprises a hub with 8 fan blades made of composite material (fiberglass) for propelling the air. This set of blades is pitch adjustable by means of a standard mechanism created especially for this purpose. The adjustment of the pitch allows the engine to operate at safely margins minimizing the operational and maintenance costs during work life of this wind tunnel. The blades (number of 8) used in the drive system were built using fiberglass. The blade manufacturing process is simple and efficient, using fiberglass lamination as shown by Fig. (12).

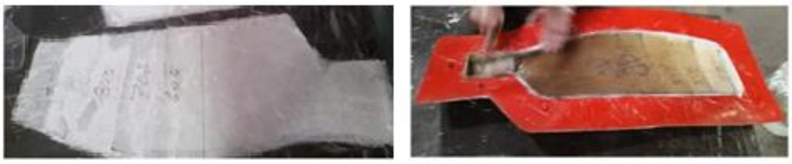

Figure 12: Fiberglass and Blanket for Blades Manufacturing (left); Lamination process in form (right).

Figure (13) shows the 8 finished blades of composite material and the view of the blades assembled in the engine.

Figure 13 - Finished Blade, Blades Set and Engine Set Front and Back Views, .

It is important to emphasize that all the structure steel parts of the tunnel were coated with anti-corrosion paint in order to have a higher durability. No “bumps” and/or surface deviation were allowable for the whole wind tunnel sections. Figure (14) illustrates the final wind tunnel completely assembled and ready for the qualification. The whole wind tunnel construction took around 12 months with all parts being under quality inspection. Any deviations from tolerances where adjusted during the fabrication process and/or even rebuild to achieve the requirements.

Figure 14: Panoramic view of the wind tunnel.

3. CONCLUSION

The design and construction of a low speed subsonic wind tunnel is somewhat not standard procedure and depends very strongly on variables such as infrastructure, flow speed requirements and mainly cost for production. In fact, cost of equipment's and parts such as drive system can really push back the design for simpler configurations. Based on that, one of the most important phases of the design is not technical but economical. A complete "part-cost" list must be specified at the beginning for initial estimates and a detailed specification must follow by stablishing contacts and in voice calls, thus refining the estimates and providing more realistic cost estimation for the whole wind tunnel conception. This wind tunnel has been built in 12 months with a specialized team of technicians which followed the original design point by point. The wind tunnel used as reference for this work is the main equipment in the CPAERO – Centro de Pesquisa em Aerodinâmica Experimental (Experimental Aerodynamics Research Center) at the Aeronautical Engineering Course at Federal University of Uberlândia – Minas Gerais, Brazil. Preliminary tests indicate that the requirements of speed and flow quality have been met with success.

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