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Subsonic wind tunnels in thermo-fluid research

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Abstract:

This thesis looks at the design and applications of subsonic wind tunnels in thermo-fluid research. The components of the subsonic wind tunnel and measurement methods are analyzed. This thesis also covers the applications of subsonic wind tunnels in aerodynamics, heat transfer and academia. Challenges regarding energy consumption and scaling effects are analyzed with recommendations for future development.

Key words: wind tunnel, subsonic, fluid mechanics, thermodynamics, sensor

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1 Introduction

1.1 Background

Subsonic wind tunnels (WT) are an essential tool for research of subsonic flows around bodies. WTs in general provide a controlled space for conducting research on how fluids act around geometries with different flow parameters. In aerodynamics and convective heat transfer research, WTs serve as validation tools for theoretical models. Subsonic WTs are also invaluable for accurately visualizing flow around bodies and how changing flow parameters impact the flow.

The role of subsonic WTs in thermo-fluid research is to provide realistic data that replicates real-world flow conditions. Since thermo-fluid research focuses on the interaction between the fluid flow and heat transfer, subsonic WTs provide a platform for testing this interaction in a controlled environment.

The rise of computational research methods such as computational fluid dynamics (CFD) software was predicted to leave WTs behind, but the incomparable accuracy of physical WTs is one of reasons why physical wind tunnel installations are still being developed and used.

1.2 Objectives of the study

The goal of this thesis is to cover subsonic wind tunnels as a whole. This thesis breaks down the key components and design considerations of subsonic WTs and evaluates the different approaches in WT design and testing. The goal is that this thesis provides a foundation for understanding subsonic WTs and their applications in thermo-fluid research.

1.3 Structure of the Thesis

Chapter 2 gives the foundation on subsonic WTs and a brief look at the history of wind tunnel development. In chapter 3, the core principles of thermo-fluid research in WT testing are covered. Chapter 4 goes over all the parts of the WT and their function. Chapter 5 goes over the applications of subsonic WTs. Chapter 6 covers challenges in subsonic WT testing and future trends. Chapter 7 concludes the thesis. In this thesis artificial intelligence has been used to correct grammatical errors.

2 Fundamentals of Subsonic Wind Tunnels

2.1 Definition and Importance

Wind tunnel (WT) is a facility or a device, where the wind is artificially produced by fans or compressed air to study flows[1]. WTs are categorized by their flow velocity and return type. Subsonic WTs operate both in the incompressible and compressible flow regime and it is determined by the flow velocity. Subsonic WTs have flow velocity up to Mach 0.8 at the test section and it is partly so that the speed of sound isn't exceeded in any experiments, creating unwanted shockwaves[2].

Since the creation of the first wind tunnel by Francis Herbert Wenham in 1871[3], the wind tunnel is still a vital part of aerodynamics testing. Wind tunnels are still the most accurate tool for studying flow around objects and heat transfer, since the complex nature of fluid mechanics and heat transfer requires extensive calculations to achieve similar results that wind tunnels can provide. Modern tools such as CFD are still not advanced or accessible enough for wind tunnels to become obsolete and this is why wind tunnels are still being built and developed.

As numerical analysis methods such as CFD continue to develop, the role of wind tunnels shift towards being a validation instrument for theoretical models[1].

2.2 Classification of Wind Tunnels

2.2.1 Wind tunnel speed regime categorization

Wind tunnels are categorized into their own respective speed regime categories, which helps us identify the corresponding wind tunnel type for a specific application. There are four main speed regimes that are considered when categorizing wind tunnels[2]:

- Subsonic ($M<0,8$) – Subcategorized ($M>0.3$ or $M<0.3$)
- Transonic($0,8<M<1,2$)
- Supersonic ($1,2<M<5,0$)
- Hypersonic ($M>5$)

The category limits are due to different flow characteristics, shock wave behavior and compressibility effects, which needs to be considered when the wind speed exceeds Mach 0.3[2]. This is caused by large enough variations in density thus resulting in compressible flow. Compressibility in flows is defined as:

$$d\rho = \rho\tau dp \tag{1}$$

Where:

$$\tau = -\frac{1}{u}\frac{du}{dp} \tag{2}$$

2.2.2 Return types

In addition to speed regime categorization, we can categorize wind tunnels based on their return types. The three main categories of return types are open return, closed return and wind shapers.

Open return wind tunnel:

The open return wind tunnel, also known as the Eiffel type tunnel, was originally created by Gustave Eiffel in 1909[4]. This type of tunnel has a closed test section, and it is open to the atmosphere from both ends of the tunnel, where it also draws the air in from. Open return wind tunnels can be either a blower type or a suction type, and this depends on where the wind generating device is located.

In figure 1 is shown a suction type open return tunnel, where the wind is generated by a fan at the end of the diffuser. Generally, suction type WTs are inexpensive to build and have a broad range of use[4]. These WTs are also excellent for flow visualization using smoke, since it does not accumulate smoke in the system and the smoke flow is easier to control compared to the blower type.

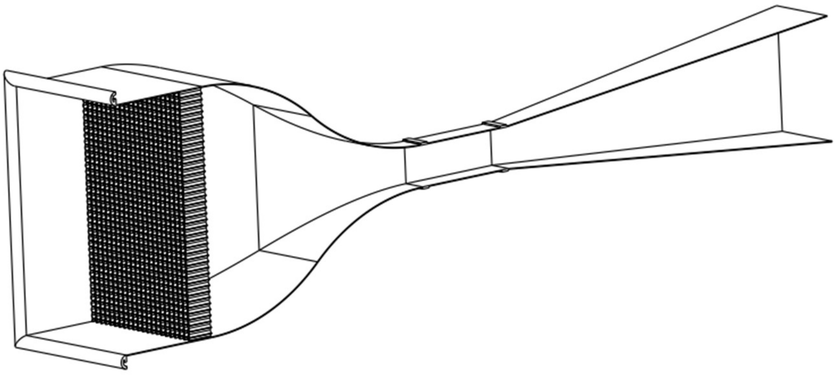


Figure 1 - NPL wind tunnel illustration. The flow goes from left to right and the straight section in the middle is the test section.

Closed return wind tunnel:

The closed return wind tunnel, also known as Prandtl or Göttingen WT, is a tunnel that is fully closed when operating[3]. This type of tunnel has a closed loop where the airflow is directed with vanes, diffusers and a contraction nozzle. In figure WHAT the general construction and parts of the closed return WT are shown. The closed construction of this WT means that the same air is circulated in the system leading to lesser losses compared to the open return WT[5]. The closed construction also creates a requirement of a cooler if the system is run for an extended period, because the fan acts as a heating element. The change in temperature would lead to inaccurate results.

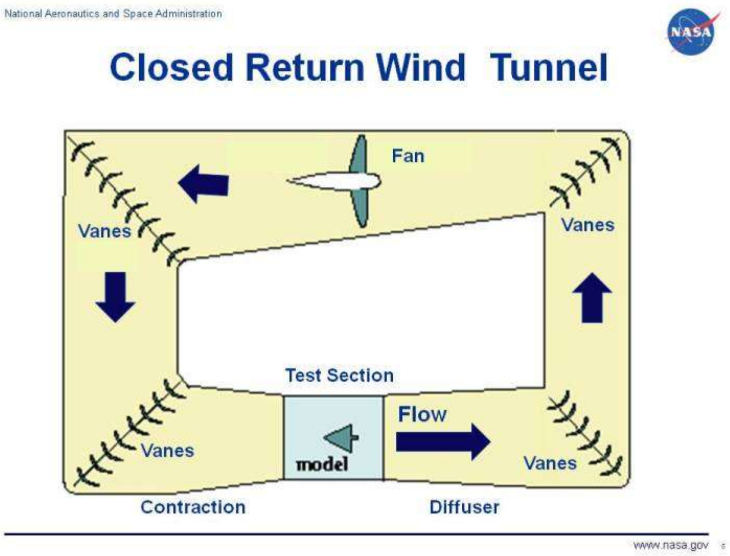


Figure 2 - Closed return wind tunnel[6]

2.3 Key Design Parameters

When designing a subsonic wind tunnel, the most important design consideration is the flow quality at the test section. To do accurate experiments and measurements, the flow needs to have a very low turbulence, and it needs to be uniform.

2.3.1 Flow uniformity

To conduct accurate measurements with subsonic wind tunnels, the flow at the test section needs to be uniform. Uniform flow means that the velocity, pressure and turbulence levels stay constant at the test section. Flow uniformity is crucial because inconsistent flow on the model can lead to unbalanced aerodynamic forces, measurement uncertainty and turbulence[7].

An accurate WT should have a uniform velocity profile at the test section where the freestream velocity is constant throughout the test section. Before conducting studies, the flow uniformity must be measured to ensure the validity of the testing results[8]. In addition to the uniform velocity profile, the yaw and pitch of the flow should be measured. Deviation in flow direction leads to uneven aerodynamic loading on the model, which leads to inaccurate results.

2.3.2 Reynolds number

The Reynolds number (Re) is essential dimensionless value in aerodynamics testing since it is used to match the dynamic similarity between the model and its real-world counterpart. Equation 3 is used to calculate the Reynolds number in the test section.

$$Re = \frac{uL}{\upsilon} = \frac{\rho uL}{\mu} \tag{3}$$

In addition to matching the dynamic similarity, the Re describes the flow regime. In WT testing, the flow is considered external. For external flows the transition from laminar to turbulent occurs at around $Re = 5x10^5$, but it is dependent on external disturbances such as vibrations, geometrical anomalies or surface roughness[9].

2.3.3 Flow quality

When combining flow uniformity and turbulence amount from the Reynolds number we get the basic definition of flow quality. High quality flow is uniform and has low turbulence and when conducting thermo-fluid research, it is required that the temperature stays constant in the test section.

The measure of flow quality is turbulence intensity that is mathematically defined as:

$$I = \frac{\sigma_u}{u_{mean}} \cdot 100 \tag{4}$$

For accurate wind tunnels the turbulence intensity should be below 1%, but usually modern wind tunnels have significantly lower turbulence intensity. The MTL wind tunnel built in 1991 at the Royal Technical University (KTH), has a measured turbulence intensity less than 0.025%[10]. Nowadays we can achieve even lower turbulence intensity values.

2.4 Governing Equations in Subsonic Aerodynamics

The governing equations in subsonic aerodynamics gives the foundation for subsonic wind tunnel design, giving a relatively accurate estimation on wind tunnel performance and flow behavior. The equations are based on traditional fluid mechanics and in subsonic aerodynamics Newtonian fluid is assumed.

2.4.1 Navier-Stokes equations

The Navier-Stokes equations explain how the momentum changes in a fluid element due to pressure gradients, viscous forces and external body forces. For incompressible flows ($M < 0.3$), the Navier-Stokes equations are written as:

$$\rho\left(\frac{\partial u}{\partial t} + u \cdot \nabla u\right) = -\nabla p + \mu \nabla^2 u \tag{5}$$

In the incompressible form, it is assumed that density ρ stays constant[11].

For compressible flows ($M > 0.3$), the Navier-Stokes equations are written as:

$$\frac{\partial(\rho u_j)}{\partial} + \frac{\partial(\rho u_j u_k)}{\partial x_k} = \frac{\partial}{\partial x_i}\left[-p\delta_{ij} + \mu\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} - \delta_{ij}\frac{2}{3}\frac{\partial u_k}{\partial x_k}\right)\right] \tag{6}$$

In the compressible form the change in density, pressure and temperature are taken into account, which is essential when calculating compressible flows[12].

2.4.2 Continuity equation

The continuity equation states that mass is conserved throughout the wind tunnel[13]. For incompressible flows, the continuity equation can be written as:

$$\nabla \cdot \boldsymbol{u} = 0 \tag{7}$$

Or in a simpler way:

$$A_1 u_1 = A_2 u_2 \tag{8}$$

For compressible flows, the assumption of constant density cannot be made. In this case the continuity equation for compressible flows can be written as:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \boldsymbol{u}) = 0 \tag{9}$$

In this form the changes in density and temperature are considered.

2.4.3 Bernoulli's equation

Bernoulli's equation is a fluid dynamics equation that is derived from the Euler equations. The Bernoulli's equation is a mathematical expression of Bernoulli's principle. Bernoulli's principle states that when the velocity increases, the pressure decreases, and when the velocity decreases, the pressure increases[11]. Along a streamline the equation needs to hold constant.

Bernoulli's equation along a streamline for incompressible flow:

$$p + \frac{1}{2}\rho u^2 + \rho g h = const \tag{10}$$

For horizontal wind tunnels, we can remove the gravitational term, which simplifies the equation to:

$$p + \frac{1}{2}\rho u^2 = const \tag{11}$$

For compressible flows, the change in density needs to be considered, so the Bernoulli's equation can be written as:

$$\frac{u^2}{2} + \int \frac{dp}{\rho} = const \tag{12}$$

3 Thermo-Fluid Principles in Wind Tunnel Testing

3.1 Fluid Flow Characteristics in Wind Tunnel Testing

Understanding fluid flow characteristics in WTs is crucial for all parts of the WT testing process. Multiple fluid flow characteristics are measured and studied during WT testing. These include flow separation, vortex formation and boundary layer development[14]. Flow separation is the phenomenon where the flow detaches from the surface which is usually caused by a problematic pressure gradient. Flow separation can lead to loss of lift, drag and reduced aerodynamic stability[14].

Vortex formation is another flow parameter that is studied in WT testing. Vortices start to form if the boundary layer on the surface of a body is instable. This can have a significant impact on the aerodynamic performance since the swirling flow has an effect on the forces acting on the body[15]. Studying and understanding vortex formation is crucial for example in automotive and aerospace engineering, where the high friction turbulent flow can have a detrimental impact on the drag of a body[15].

As previously mentioned, the Reynolds number has an influence on the flow regime inside the test section. External factors such as vibration can cause turbulent flow with low Reynolds number, and this goes the other way also. If there are no external disturbances, it is possible to have laminar flow with high Reynolds number. Matching the Reynolds number is crucial for achieving dynamic similarity between the model and its real world counterpart[9].

Boundary layer is related to both the flow separation and turbulence. The boundary layer always starts off as laminar but can transition to turbulent or stay laminar depending on the surface roughness, flow velocity, Reynolds number and the surface pressure gradient[17].

3.2 Heat Transfer Considerations

Subsonic WTs are widely used for studying forced convection. This type of heat transfer occurs when airflow travels over a surface thus causing thermal energy to transfer. For example, forced convection experiments are used to design cooling systems and to measure thermal insulation performance. The rate of convective heat transfer depends on free stream velocity, flow temperature, turbulence and the geometry of the body[19].

Convective heat transfer is defined by Newton's law of cooling found in equation X. In this equation, the heat transfer coefficient h is heavily affected by the Reynolds number and flow regime[9].

$$q = hA(T_s - T_\infty) \tag{13}$$

In convective heat transfer experiments, the thermal boundary layer and its development is studied. The thermal boundary layer has a temperature gradient that forms between the surface and the freestream flow. This layer results in thermal resistance, where the thickness and flow regime have a significant impact on the heat transfer rate[9], [20]. For example, turbulent, high Reynolds number flows have a better cooling capability compared to a laminar flow, but the analysis of a turbulent flow is a lot more complex[20].

3.3 Experimental vs. Computational Analysis

With improvements in computational technologies, CFD analysis has set its place as one of the primary testing methods in aerodynamics and thermal testing. In modern facilities, physical WTs and CFD software are both used in analysis and design tasks to streamline and speed up the workflow. These two methods used together provide a strong platform for testing where both methods support each other and they can be used for result validation[7].

Physical WT testing provides an accurate representation of aerodynamic and thermal properties of the flow over a body. WTs can replicate real-world flow phenomena accurately, thus making them more accurate than CFD analysis. Attributes that can have an impact on the flow such as surface roughness, surface anomalies and flow separation are simplified or not considered in CFD analysis. Physical WTs reveal all possible problems that come up in testing with either flow visualization methods or sensors.

The progress made in computational methods has made CFD software an essential tool in the design and research of aerodynamic models and thermal testing. The accessibility of CFD allows for quick design iteration and extensive result visualization, which is essential in industries such as the automotive and aerospace industries. Testing complex geometries in physical WTs is expensive and time consuming, due to the manufacturing of the model and the test preparation. CFD bypasses these problems, making computational analysis also significantly cheaper compared to physical testing.

Modern facilities use hybrid models, where physical WTs are used to validate the results from CFD analysis. The early iterations in the design process are tested with CFD software to reduce the capital and time consumed in the design process. Then the final iterations are done using the results gotten from physical WTs to ensure the accuracy of the results and to reveal possible problems that the CFD analysis did not show[21].

4 Design and Components of a Subsonic Wind Tunnel

4.1 Settling chamber

The settling chamber is the starting point for the flow in both open and closed return WTs. The function of the settling chamber is to reduce flow irregularities such as vortices, turbulence, swirling effect, spatial non uniformity and low frequency pulsation[4].

The construction of the settling chamber consists of honeycomb structures, mesh screens or the combination of both. Multiple different types of honeycomb structures are used to reduce turbulence out of which the most widely used shapes are found in figure 3; square, circular and hexagonal. The hexagonal honeycomb is optimal for use in wind tunnels, since it has the lowest pressure drop coefficient[4].

The length of the honeycomb cell should be 6 to 10 times the hydraulic diameter of a single cell in the honeycomb for optimal performance[4]. Studies show that the ratio of 5 to 10 removes the lateral turbulence from the flow, but to ensure accuracy and reliability minimum ratio of 6 is used.

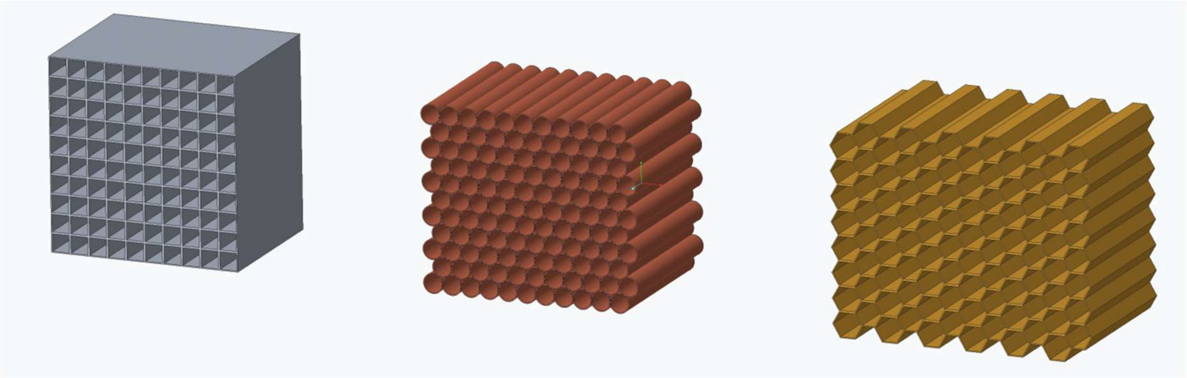


Figure 3 - Honeycomb structures used in wind tunnel settling chambers

The mesh screens in the settling chamber serve a similar purpose to the honeycomb panels, which is to reduce turbulence and make the flow uniform. These screens also catch unwanted debris in open return WT applications. The most important parameter in these screens is the porosity, which defines the ratio between the total area of the screen and the area covered by the mesh[22]. These screens are identified by the diameter of the wire used to make the mesh and the mesh size[22].

4.2 Contraction and Diffuser Sections

On each side of the test section, we have the contraction and diffuser sections. These are essential sections, since they direct and condition the flow to be high quality at the test section. With careful design choices and calculations, it is possible to reduce the need for excess screens and filters before the contraction nozzle, thus reducing pressure losses.

4.2.1 Contraction

There are multiple design considerations when it comes to designing an accurate contraction nozzle for a subsonic wind tunnel. With careful design, it is possible to reach very high flow quality with only the contraction nozzle, reducing pressure losses caused by conditioning screens before the nozzle. The purpose of the contraction nozzle is to direct and accelerate the flow, and to reduce turbulence.

There are different types of nozzle contours that all strive to achieve the nozzle requirements but vary in performance and ease of construction. The most used contours in subsonic WTs are:

- Vitoszinski
- 2nd order polynomial
- 5th order polynomial
- Bell contour.

These contours are seen plotted in figure 4. Each of these contours have different properties regarding flow stability and acceleration. The 5th order polynomial and the bell contour are widely used in modern high-performance facilities due to their smooth acceleration[23].

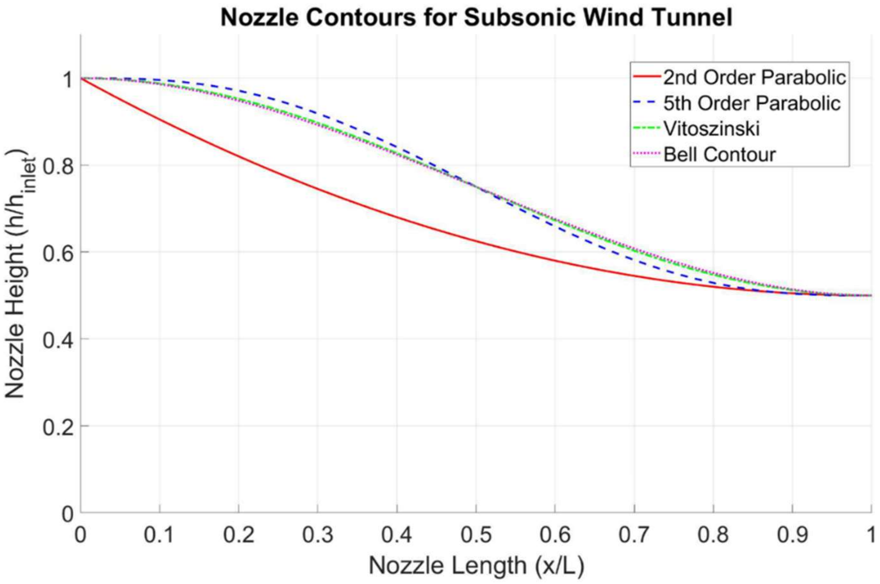


Figure 4 – Most used contours in subsonic wind tunnels plotted with MATLAB

The contraction ratio for smaller WTs is between 6 to 9, while larger WTs use a contraction ratio between 7 to 12[24]. Higher contraction ratios help reach higher quality flow but are more expensive due to construction costs.

4.2.2 Diffuser

The diffusers function is to slow down the flow after the test section and this causes the static pressure in the system to recover[25]. The diffuser also reduces stress and load on the drive system[4]. Like the contraction nozzle, the diffuser has a ratio of area (AR) that specifies the increase in cross-sectional in the diffuser. The optimal AR for a subsonic WT is between 2 and 5. Another parameter to take into consideration is the expansion angle. The ideal expansion angle for conical diffusers is 3 degrees, while wide-angle diffusers use much larger 22.5 degree expansion angle[7].

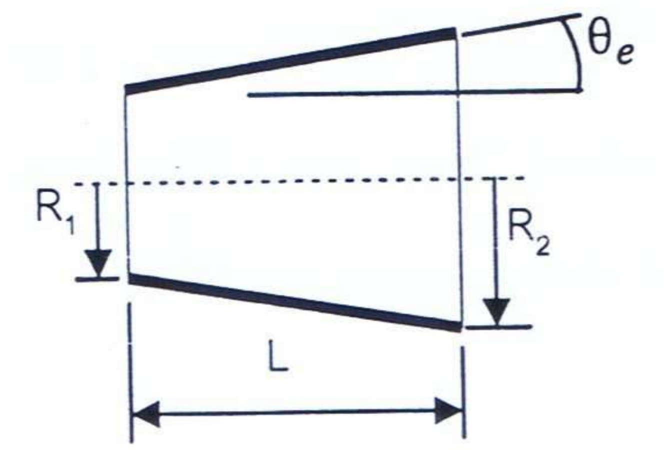


Figure 5 - Diffuser geometry with expansion angle visualized[26]

4.3 Test Section

The test section is the part of the WT, where the studies are conducted, thus requiring the highest quality flow in the WT. Maintaining steady flow is the most important feature when designing the test section for a wind tunnel. The continuity equation states that to maintain a steady flow i.e. no flow parameter changes, the cross-sectional area of the test section needs to hold constant[13]. The length of the test section should be between 0.5 and 3 times the size of the inlet cross-sectional area[27]. If the test section is too short, the flow isn't able to develop after the contraction nozzle and if the test section is too long, the flow suffer from boundary layer growth[28].

Subsonic WTs have a wide range of test section geometries depending on the application, but rectangular shaped test sections are often used due to their construction simplicity. For a rectangular test section the ratio between the height and width should be between 1 and 1.4[25]. The test section should also be designed so that the blockage caused by the objects that will be studied, will not exceed 10% of the test sections cross-sectional area[25].

4.4 Drive System and Fan Assembly

The fan is the core part of the WT and it is important to design the construction of the fan carefully to maximize the performance of the fan and to reduce possible turbulence caused by the fan blades.

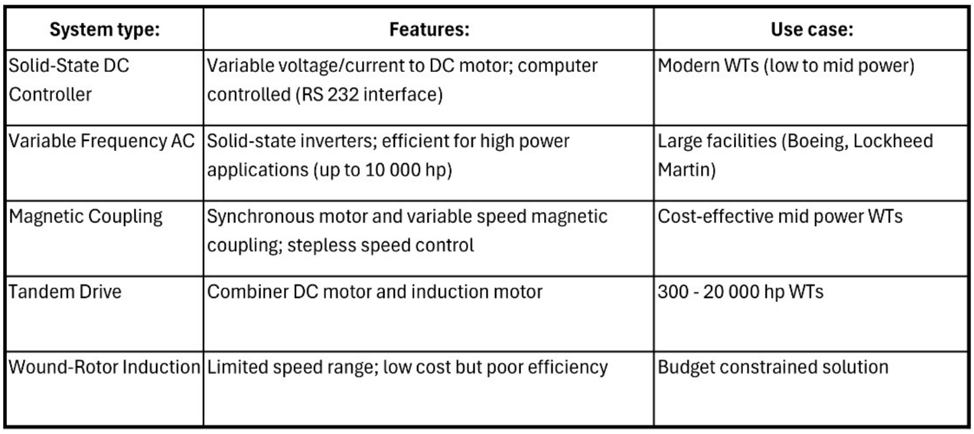
In open return WTs, the fan is usually placed downstream of the test section at the end of the diffuser to reduce turbulence introduction to the test section. Blower type WTs place the fan upstream of the test section, but this setup requires a significant amount of flow straighteners and conditioners such as honeycombs and screens thus increasing losses.

In closed return WTs the fan is placed as far away from the test section as possible. This consideration allows the flow to be effectively conditioned before the test section and this placement also lowers the fan noise and vibration at the test section[7].

The fan blades that are used in subsonic WTs call for high lift to drag ratios that are from 60 to 100[7]. For example, the RAF type D airfoil is able to have a lift to drag ratio over 80[7]. To vary the wind speed and flow characteristics the fan blades usually have a pitch adjustment to control the blade angle. The blade angle pitch in combination with RPM adjustment of the drive unit is how the wind speed is varied in the WT.

Drive systems used in modern subsonic WTs are electrically powered and the type of system depends on the size of the WT and the budget of the construction. In table 1 is listed the most used drive systems in subsonic WTs.

Table 1 - Drive system comparison



System type:	Features:	Use case:
Solid-State DC Controller	Variable voltage/current to DC motor; computer controlled (RS 232 interface)	Modern WTs (low to mid power)
Variable Frequency AC	Solid-state inverters; efficient for high power applications (up to 10 000 hp)	Large facilities (Boeing, Lockheed Martin)
Magnetic Coupling	Synchronous motor and variable speed magnetic coupling; stepless speed control	Cost-effective mid power WTs
Tandem Drive	Combiner DC motor and induction motor	300 - 20 000 hp WTs
Wound-Rotor Induction	Limited speed range; low cost but poor efficiency	Budget constrained solution

In closed return WT applications, the heating caused by the fan and drive system needs to be considered. When ran for extended period of time the drive system starts to introduce heat into the system, which is why heat exchangers are used to keep the temperature constant inside the WT[7]. Another challenge with the fan and drive system is the vibration. To eliminate the risk of flow quality reduction, the fan and drive system should be separated from the rest of the WT so that vibration induced disturbances are removed.

4.5 Instrumentation and Measurement Techniques

In wind tunnel testing there are multiple values and parameters that are monitored while doing experiments to get the most data out of a single run. The evolution of WTs means that more and more sensors and data instruments are used in WTs, which makes the modern subsonic WT very intricate experimental device. This chapter will go over the measurement instruments and data processing tools found in subsonic WTs.

4.5.1 Pressure and velocity measurement in the test section

Pressure and velocity measurements are vital for wind tunnel design validation and flow analysis in the test section. Pressure is one of the parameters that is used to determine the flow state in the test section to ensure that the measurements are valid. The following instruments and sensors are used to measure the pressure and velocity in subsonic WTs.

Pitot-static tubes:

Pitot-static tubes measure the total and static pressure in the WT test section, providing two pressure measurements at a single point. For incompressible cases, i.e. M < 0.3 Bernoulli’s equation can be used to calculate the flow velocity from the two pressures.

$$u = \sqrt{\frac{2(p_{total} - p_{static})}{\rho}} \tag{14}$$

Where the dynamic pressure p_d is shown as $p_{total} - p_{static}$.

In figure 6, a pitot-static tube is shown where the hole at the tip of the tube measures the total pressure of the flow while the pressure tap at the top measures the static pressure[11].

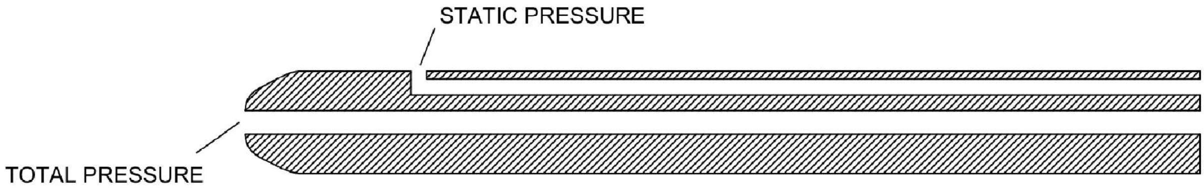


Figure 6 - Pitot-static tube cross-section

Pitot-static tubes and especially pitot tubes that doesn’t measure the static pressure of the flow are combined into pitot rakes which is an instrument that combines multiple tubes into one device[29]. These rakes measure the velocity profile across a plane[29]. While pitot tubes are inexpensive and fast devices to measure the pressure and velocity in the test section, they disturb the flow, which could lead to inaccurate measurements, especially in a rake configuration[29].

Pressure taps are drilled or flush-mounted holes that are perpendicular to the surface that it’s mounted to. These taps are connected to pressure transducers that measure the local static pressure. In aerodynamics experiments these taps are installed on models to measure the lift, drag and flow separation on a model. This makes them especially useful for wing design validation. Pressure taps can also be installed on the walls of the test section to provide data about static pressure at a specific point in the test section.

For velocity measurements in the test section, hot-wire anemometers (HWA) are also used. The HWA found most in WT testing is a constant temperature anemometer (CTA). CTA is an anemometer that has a heated metallic filament that is cooled by the flow that it’s placed in and the flow velocity is calculated by the amount of current required to keep the temperature of the filament constant[30]. Compared to other velocity measurement instruments, the HWA is less expensive compared to modern technologies. HWAs also have an edge over some modern technologies such as laser doppler anemometry (LDA) in terms of sample rate. LDAs sample rate is limited to 30 kHz, but most HWAs have a sample rate from 20 to 50 kHz with some models reaching rates over 100 kHz[30].

Laser Doppler Anemometry (LDA) is a non-intrusive optical velocity measurement technique. LDA uses a laser beam that is split into two beams and then re-focused to intersect at a specific point. This point creates an intersecting pattern of two laser beams, where the moving particles are then detected with a photodetector[31]. The flow velocity is calculated with the frequency of particles crossing the intersecting point[31]. Compared to Particle Image Velocimetry (PIV), LDA requires a lot less post processing and calibration.

Particle Image Velocimetry (PIV) is another non-intrusive velocity measurement technique, that can capture the flow field and localized velocities in the measurement area. PIV works by generating short laser light pulses which illuminate the particles in the flow. These particles are tracked with a high speed camera to track their movement and the flow velocity is calculated by measuring the amount of distance a particle has traveled between two pulses[31]. Compared with other velocity measurement techniques, PIV gains an advantage over other techniques due to its capability to measure velocities in the whole two-dimensional plane.

4.5.2 Temperature measurement

Measuring temperature in a WT is essential when validating WT design and when conducting experiments that investigate thermal effects. Temperature measuring instruments are used to maintain constant temperature in the test section, measure heat transfer and surface heat flux for example.

Thermocouples are used in wind tunnels since they are inexpensive, robust and cover the whole temperature range that can be found in a WT. The thermocouple is two wires made from different metals joined together. When temperature is being measured the two wires create a voltage difference based on the Seebeck effect[32]. This voltage difference increases when the measured temperature increases. Thermocouples can be placed in the test section to measure the free flow temperature, or they can be installed into the model to measure the surface temperature and heat transfer. Since thermocouples are inexpensive, multiple sensors can be installed to a model to map out the temperature distribution of the model.

Resistance Temperature Detectors (RTD) are temperature sensors that measure the temperature with a resistance wire that has a change of resistance based on the temperature[33]. RTDs are more precise and have less signal drift compared to thermocouples, but they are slower in response time. RTDs have been rising in WT usage, since they have become less expensive and more robust. Also, the development of faster and more accurate RTDs have caused them to start to replace thermocouples.

Infrared Thermography (IRT) is a non-intrusive temperature measurement technique that optically measures the temperature from thermal infrared radiation. IRT cameras can monitor the temperature in a three-dimensional space, which makes it excellent for heat transfer studies and thermal boundary layer analysis[34]. In wind tunnels IRT is used to analyse convective heat transfer, cooling studies and laminar to turbulent transition[34]. IRT systems require some extra consideration compared to other temperature measurement systems. For example, the IRT system requires accurate calibration when installed and the ambient thermal radiation must be minimized or kept constant to ensure accurate results.

4.5.3 Flow visualization techniques

Flow visualization is used in subsonic WTs to visualize and study vortex formation, boundary layers, flow separation and transition phenomena. Visualization helps researchers understand flow behavior, which in turn speeds up the design process of models for example. Flow visualization technique is chosen by the accuracy and resolution needed.

Non-optical methods:

Smoke tracer visualization is one of the oldest visualization techniques in WTs but still remain extremely popular in modern WTs. In smoke visualization a stream is inserted into the flow, which then follows the freestream inside the WT[35]. These streams are useful for studying vortex structures and turbulence formation and in airfoil design the smoke stream reveals possible flow separation zones which leads to reduced lift. In figure 7 the flow around the airfoil is visualized by the smoke streams.

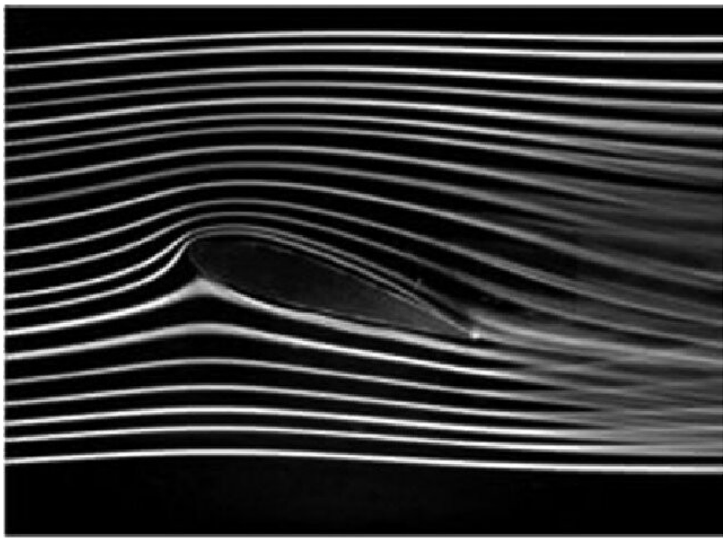


Figure 7 - Flow visualization with smoke[36]

For simple surface phenomena studies, small lightweight threads called tufts can be used. These tufts are attached to surface of the model, where they visualize the flow field[35]. Depending on the experiment’s parameters, the material and diameter of the tuft needs to be considered. In fast flow conditions fluorescent tufts with UV light is used to visualize the movement of the tufts better[35].

Compared to using tufts, the surface oil technique provides a more accurate representation of flow at the surface of a body. In surface oil technique a layer of pigmented oil is applied to the surface of the body, which then reveal the surface flow pattern when subjected to wind[35]. This flow pattern shows the streamlines and the flow attachment and separation points. In figure 8 fluorescent oil shows the surface flow patterns on a body.

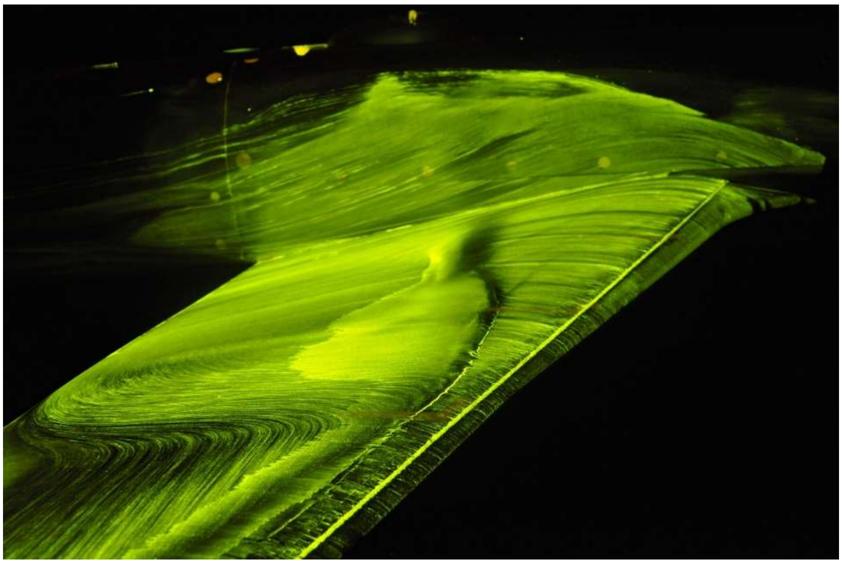


Figure 8 - Surface oil visualization method[37]

Optical methods:

Shadowgraph is the oldest optical non-intrusive flow visualization method. This method is based on the deflection of light that is caused by the second derivatives of the refractive index, which change depending on the density of the fluid[38]. The shadowgraph setup requires a light source, lens system and a projection screen to display the flow. Shadowgraph method is mainly used in compressible flows to reveal temperature and density changes with large gradients[38].

The Schlieren method is the improved version of the shadowgraph method. The Schlieren method is more sensitive due to it capturing the first derivatives of the refractive index[38]. With this technique, it is possible to capture more subtle changes in the flow making it far greater for subsonic applications compared to the shadowgraph. The Schlieren method is used for analyzing boundary and shear layers, heat transfer effects and laminar turbulent transitions. While still being more complex to calibrate and build, the Schlieren method is the most used non-intrusive method used to visualize flows due to its accuracy and clarity[38].

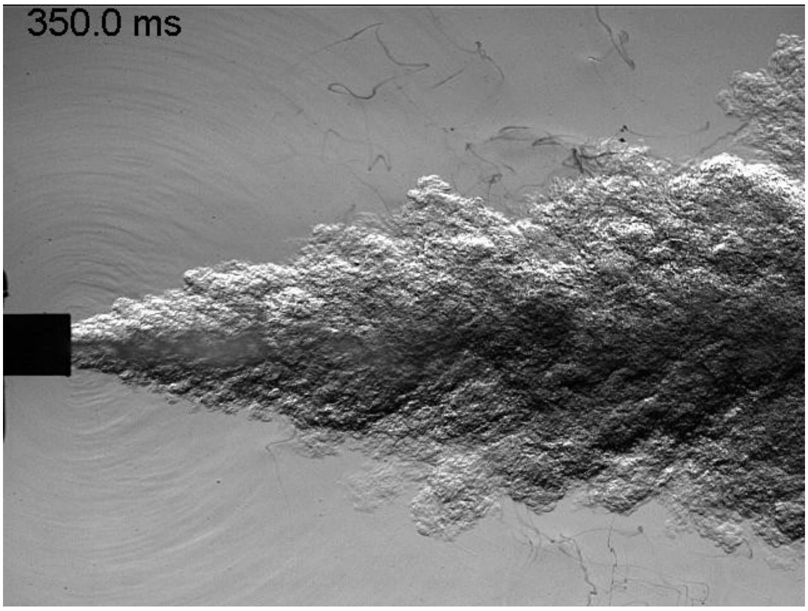


Figure 9 - Schlieren method flow visualization[39]

4.5.4 Data acquisition systems

Data acquisition systems (DAQ) are used to convert and log all the data received from the sensors. Most of the data gotten from these sensors is analog so DAQs act as a bridge between the analog sensor data and the computer. DAQs are responsible for timecoding the data so that in the analysis the data from all the sensors is synchronized.

DAQ systems have three main functions: signal conditioning, A/D conversion and timecoding. In the signal conditioning the analog signals from the sensors are amplified and filtered to remove unwanted noise or aliasing. After this the analog signals are sent to the analog to digital converter. The digital data gotten from the A/D converter is then displayed on the computer, ready to be analyzed.

For the data to be useful, synchronization and timecoding of the data is extremely important in WT testing, especially if the model is moving or the flow parameters are known to change. Software like National Instruments LabVIEW then displays the gotten data and provides the platform for signal analysis[40].

4.5.5 Calibration and uncertainty analysis

Accurate measurements in WT testing depend heavily on instrument calibration. In modern WTs there are large amounts of different sensors and instruments so individual instrument calibration and traceability are extremely important for the data to be reliable. Depending on the sensor or instrument, the calibration should be done with reference values and instruments according to the calibration standard of the sensor. The calibration must be completed so that the data can be trusted. Modern DAQs have inbuilt calibration algorithms, but all the sensors and instruments need manual calibration at regular intervals.

While calibration is vital to get accurate data, there is a possibility of data deviation from the sensors and instruments. This must be considered with uncertainty analysis. The total uncertainty for the measurement system for the WT is calculated with the root sum square method. In this method there are two types of uncertainty. Type A, which is the random variation in results gotten from test runs and type B, which is the uncertainty given by the manufacturer. The total uncertainty can be calculated:

$$U_{total} = \sqrt{U_A^2 + U_B^2} \tag{15}$$

After the whole system has been calibrated, the values should be documented so that all the values are traceable. Documentation is also crucial because the calibration values and uncertainty analysis need to be presented with the results obtained from the WT experiments.

5 Applications in Thermo-Fluid Research

5.1 Aerodynamic Testing

Subsonic WTs are widely used in aerodynamics testing to optimize and validate designs and to reveal flow disturbances that CFD experiments have not revealed. The aerodynamics testing focuses on analyzing the aerodynamic properties of a model.

The force balance method is widely used as a simple lift and drag measurement method in aerodynamics testing. In the force balance method, the model is fixed into the test section with force sensors that essentially measure the X- and Y-axis forces i.e. lift and drag[41]. The results obtained from WT testing give the truth about a model's aerodynamic properties, like seen in the experiment done in the university of Belgrade. At the university they tested the aerodynamic performance of the Boeing 787 aircraft and the results followed the expected force curves[41].

In aircraft engineering, it is vital that the aircraft designs are validated in a WT to reveal possible flow separation and stall points on the wings of the aircraft. This is done with the aforementioned force balance method and with pressure distribution analysis, which helps to identify aerodynamic problems such as stall onset and boundary layer detachment[41], [42], [43]. The pressure distribution analysis is also vital to identify flow detachment and reattachment points on the model, which can lead to flow disturbance and uneven pressure distribution, thus leading to reduced aerodynamic performance[43].

Wind tunnels are also used to optimize airfoil profiles. Airfoils are used in nearly every subsonic application where air needs to be moved, or where air is used to generate motion. These applications include aircraft wings and fan blades. For example, wind turbine blades are tested to optimize the airfoil to maximize lift while minimizing drag to increase the efficiency of the wind turbine blade.

The DU 97-W-300Mod airfoil made for wind turbines was tested in the ONERA F2 wind tunnel to study flow separation and lift performance at varying Reynolds numbers[42]. The study found that the airfoil was able to maintain a stable lift curve up to a moderate angle of attack before stalling[42]. This data is extremely useful for aerodynamic optimization of models.

5.2 Heat Transfer Studies

In addition to aerodynamic testing, subsonic WTs are used in heat transfer studies, especially in experiments that are focused on forced convection. In forced convection, a fluid in forced motion is used to either cool or heat a surface depending on the application. This is why WTs are a useful tool for heat transfer studies, since it is possible to control the flow parameters, which allows for accurate measurements of heat transfer parameters.

Convective heat transfer is usually studied in WTs by inserting a heated object into the test section and then measuring the temperature response with temperature sensors mentioned above. From these tests, the local heat transfer coefficient can be calculated for specific parameters and the effect of freestream velocity and turbulence can be analyzed[44].

Subsonic WTs are extensively used to analyze the cooling performance of components. In a study by Wadih Naim, a subsonic WT was used to analyze different conductor shapes on their ability to remove heat in a crossflow. The study concluded that the angle of attack and the conductor surface had the biggest impact on the heat removal ability[45]. These results were used to improve the Dynamic Line Rating (DLR) systems in electric power transmission[45].

Thermal boundary layers are also studied with WTs to analyze the boundary layer development and the thermal gradient. In a study by Liu and Komiya, a WT was used to analyze the thermal boundary layer on a flat plate under forced convection[46]. In the experiment a cooled and heated plate was placed in the WT and their average heat transfer rates were measured in both high and low-speed flows. They concluded that the heat transfer rates were similar at higher velocities but in a low-speed flow the buoyancy effects caused a lower heat transfer rate due to airflow interference on the surface[46].

5.3 Industrial and Academic Applications

In the aerospace industry, subsonic WTs are widely used to optimize the aerodynamic performance of subsonic aircraft and other aerial vehicles. The aerospace industry is also the leading industry in the development of subsonic wind tunnels, since the need for higher efficiency aircraft is growing continuously. Airframes are becoming increasingly complicated so the need for wind tunnels, where parameters such as lift, drag and flow separation can be measured in varying flow conditions is high. In modern airframe testing, WTs are a tool to verify CFD simulations and to study the stall behavior of the airframe.

The automotive industry uses subsonic WTs to improve aerodynamics and to study efficient cooling solutions. Vehicles are extensively tested in WTs to reduce drag and to increase downforce and stability. Whether it is for fuel saving purposes or for higher performance. Aero components such as spoilers, diffusers and underbody designs are optimized in WTs to verify the results gotten from CFD simulations. In electric cars the need for highly efficient cooling systems has increased WT usage in the automotive industry. Managing battery and engine temperatures is critical for safety so passive cooling designs are extensively studied to optimize the cooling of these components.

In civil engineering, subsonic WTs are vital for the testing of skyscrapers, bridges and other large buildings. The wind loading on large structures can be massive so to prevent uneven pressure distribution the models are tested in a WT to optimize the building to remove pressure hotspots. WTs are also used in civil engineering to analyze city layouts and how they can cause wind buildup or unexpected wind patterns that can negatively affect the ventilation systems in buildings.

Academia uses subsonic WTs in education and research. Wind tunnel experiments help students understand the core concepts in fluid mechanics and thermodynamics. For example, the visualization of turbulence and its impact to drag of an airfoil is an excellent way of letting students learn hands on. In academia, wind tunnels are also widely used in research to conduct aerodynamic and thermal research.

6 Challenges and Future Trends

6.1 Limitations of Subsonic Wind Tunnels

Subsonic WTs have their limitations, despite being a multiuse instrument. The first problem with subsonic WTs is the scaling effects that are introduced when testing scaled down models. To study the aerodynamics of scaled down models, the Reynolds number needs to be considered, which can be difficult. This problem arises especially at low freestream velocities and when testing small models. If the Reynolds number is not matched correctly the results obtained from the experiment will not match real world conditions.

Another limitation is the blockage ratio of the test section. As previously mentioned, the blockage ratio of 10% should not be exceeded, since this causes disturbances in the freestream flow. The disturbed flow can be corrected with blockage corrections, but to get as accurate results as possible, the ratio of 10% should not be exceeded. In turn the blockage ratio limits the size of the that can be tested in the test section, thus making it difficult to match the Reynolds number.

While subsonic WTs are very accurate, they are not the fastest tool to test designs. The time required for building the model and setting up the experiment is significant, so iterating the design is a time-consuming process if done purely with a WT. This is why CFD is used in early iterations and then the final modifications are tested in a WT.

6.2 Advances in Measurement Technologies

The improvement of measurement technologies has brought more accurate, non-intrusive measurement instruments and sensors into WT testing. Technologies such as PIV and LDA have improved massively over the last decade, which is why these technologies are widely used in WT testing[47].

New optical measurement methods are more accurate than their predecessors, while also being non-intrusive to avoid disturbing the flow in the test section. Compared to traditional non-optical measurement methods, these new optical methods can visualize and measure boundary layer development, turbulence structures and vortex shedding, which all would be difficult to measure with traditional methods.

Higher speed multichannel DAQ systems have improved data synchronization and measurement accuracy, since these systems can collect data from more sensors and have higher sampling rates[48]. Higher speed systems have enabled more transient experiments and more complex studies with multiple changing parameters.

6.3 Integration with Computational and AI-Based Approaches

Modern wind tunnel installations use hybrid systems where both the physical wind tunnel and CFD are used in the same project. Due to CFDs ease of use and low running costs, the early design iterations are tested with CFD and when these tests provide satisfactory results, the fine tuning is done with the wind tunnel. In installations where both CFD and WT are both used, the wide feature set of this combination allows the design team to make better design choices faster[21].

When designing complex models where the flow conditions change over time the WT validated designs are tested again in CFD software to simulate changing flow conditions. These parameter sweeps give valuable data on how the geometry is affected in different flow speeds, temperatures or turbulence values[21].

The use of artificial intelligence (AI) and machine learning (ML) has significantly increased over the recent years in WT testing. AI and ML have made their way into DAQ systems and CFD software to speed up the testing process and to help with data analysis. To speed up the testing process, AI can suggest test conditions and flow parameters to reduce the downtime caused by the setup process[49]. AI models trained with data gotten from WT testing can be used for a variety of applications. These applications include:

- Predictions on aerodynamic and thermal performance[49]
- Identifying patterns or anomalies in the data gotten from the WT testing[49]
- Optimizing WT settings or model geometries based on real time feedback[49]

In the future, smart control systems controlled with AI could be used to adjust flow parameters based on the real time data received from the sensors[49]. This would help researchers create dynamic testing environments where the flow behavior around the model could be analyzed more extensively.

6.4 Energy Efficiency Considerations

Wind tunnels require a significant amount of energy to run, especially large facilities and open return WTs. As the world becomes more conscious of energy consumption, WT facilities must evaluate their energy sources and drive systems to meet the future demands. Energy consumption isn’t only a sustainability problem, but also a development opportunity to build higher performance WTs with efficient drive systems.

One method that can reduce energy consumption is to use variable frequency drives (VFD) in the motor. Compared to traditional constant-speed drives, VFDs can adjust the speed dynamically, which reduces the amount of energy used. Studies have shown that use of VFDs can significantly reduce the energy consumption which reduces the greenhouse gas emissions caused by WT facilities[50].

In addition to using more efficient drive systems, WT facilities should integrate renewable energy as their energy source. The immense energy requirement of WT facilities necessitates that hybrid renewable energy systems are used to produce enough electricity to run large test facilities. In hybrid renewable energy systems, two or more energy sources are combined to achieve clean energy for energy-intensive test facilities[51]. Depending on the geographical location of the test facility, hydropower and solar power have been found to be the most effective for energy-intensive applications[52]. While these hybrid renewable energy systems are still under development, the research done in smart grid technology makes hybrid systems more appealing to WT test facilities.

7 Conclusion and Recommendations

7.1 Summary of Key Findings

This thesis went over the foundations, key design principles, measurement methods and instruments, and applications of subsonic WTs in thermo-fluid research. Subsonic WTs remain an essential tool for study of flows around objects due to their accuracy. Software based solutions such as CFD continue to develop, but as of now, the simplifications done in CFD analysis means that result validation with physical WTs is still necessary. The key findings of this thesis are:

- Understanding flow uniformity, turbulence and Reynolds number is essential for conducting accurate research
- Creating theoretical model of the flow throughout the WT with the governing equations is crucial in designing a subsonic WT that meets the desired accuracy
- Since flow uniformity and low turbulence is essential for accurate and repeatable measurements, the design of the settling chamber and the contraction nozzle is crucial
- Optical measurement methods are preferred because they are more accurate and they do not disturb the flow, which could lead to inaccurate results
- Subsonic WTs have a wide range of applications and remain an essential tool for testing in multiple industries

7.2 Implications for Future Research

Modern subsonic WT installations are highly accurate and difficult to improve on, so the future development of subsonic WTs should focus on energy efficiency and the improvement of low-cost facilities. The high cost of subsonic WT installations means that the performance and accuracy of the installation is often limited by the budget. Research on how flow quality could be improved without increasing the complexity of the installation would benefit organizations that are mainly limited by the budget. Discoveries in this research could lead to higher performance solutions for larger facilities

Energy efficiency needs to be considered due to the growing energy crisis, so higher efficiency drive systems need development. Subsonic WT facilities require a significant amount of energy to operate, so research and development in drive systems and sustainable energy is essential to ensure that WT installations have enough energy to operate in the future.

7.3 Recommendations for Wind Tunnel Design Improvements

The research done for this thesis has brought improvement ideas:

- Meticulous design of the contraction section should be done before relying on the settling chamber for creating flow uniformity
- Implementation of modular sensor systems to reduce setup time and to allow the addition of new sensors in the future
- If possible, using closed return WTs should be favored to reduce the amount of energy required for the operation of the WT

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