Classification and application of wind tunnel experiment

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Abstract. The main purpose of this paper is to introduce the wind tunnel experiment in different aspects. This paper firstly presents the designs and classifications of wind tunnels. The wind tunnels will be classified as low-speed wind tunnels, aeroacoustic wind tunnels and subsonic wind tunnels. Under the classification of low-speed wind tunnels, there are open return wind tunnels and closed-circuit wind tunnels. The structural designs of topology optimization, topography of optimization, size optimization, free size optimization are introduced and compared. Traditional and modern measurements of the fluid are listed and given detailed examples. The applications of wind tunnel design in stress, dynamic and aeroelastic analysis, aerospace, cars and high-speed trains and environment and buildings will be introduced. The paper will analyze current challenges such like the reliability of wind tunnel data validating and calibrating numerical models, achieving sufficiently low turbulence intensity (TI) and background noise levels and similitude constraints when scaled models being tested. At last, the development trends in this field ‘ll be introduced and future outlook will be predicted.

Keywords: Wind Tunnel Experiment, Design, Low-Speed Wind Tunnel.

1. Introduction

Wind tunnels are devices that enable researchers to study the flow over objects of interest, the forces acting on them and their interaction with the flow [1]. The importance and development background of the study of wind tunnel experiment will be introduced. As a quite widely employed and cost-effective technique, the wind tunnel experiment is used in a wide variety of applications. The article will introduce different types of wind tunnels used in the aerodynamic field and acoustic research. Specifically, wind tunnel experiments play an important role in aerodynamics and acoustic research. In the field of aerodynamic, wind tunnels have been used to facilitate the design of aircrafts [1]. Wind tunnel experiments can also be used in the field of aeroacoustics research. For example, a type of open jet, blow down wind tunnel is intended for the measurement of airfoil trailing edge self-noise but can be extended to other aeroacoustic applications [2].

The paper will introduce different types of wind tunnels that are mainly used in these two fields and classify these designs. The designs are listed: the IVK Aero-Acoustic Wind Tunnel, which has a very low self-noise level; The D5 aeroacoustics wind tunnel at Beihang University , which is a newly commissioned small-scale closed-circuit wind tunnel with low turbulence intensity and low background noise (a kind of low-speed wind tunnel) and so on. The structural designs like topology optimization, topography optimization, size optimization, free size optimization and so on are introduced and compared. Traditional and modern measurements of the fluid or the flow will be listed and given detailed examples. The applications of wind tunnel design in stress, dynamic and aeroelastic analysis, aerospace, cars and high-speed trains and environment and buildings will be introduced supported by specific data sets. At last, the paper will analyze current challenges and development trends in this field and predict future outlook.

2. Wind Tunnel Designs and Classifications

2.1. Low-Speed Wind Tunnel

The open-circuit or NPL arrangement is a basic type of low-speed wind tunnel in FIG.1.

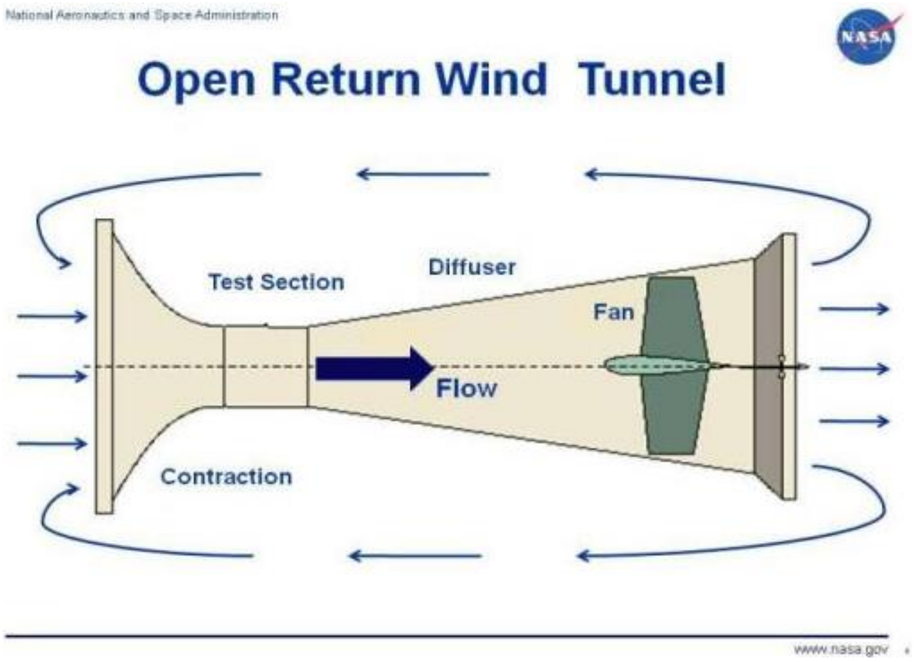

Figure 1. Open returen wind Tunnel from website of NASA

This type of tunnel is also called an Eiffel tunnel. This type of wind tunnel draws air from the surrounding environment, channels it through a test section where an object is placed and then exhausts it. Compared to a closed-circuit tunnel (another type of low-speed wind tunnel), this design is simpler and cheaper to build. It is a superior design for propulsion and smoke visualization. They also suffer less from temperature changes (mainly because room volume > tunnel volume) and the performance of a fan fitted at the upstream end is not affected by disturbed flow from the working section [3]. It doesn't build up any exhaust gases, but it also has some drawbacks. It costs a lot to run because the fan has to keep speeding up the air moving through the tunnel all the time. When the air flows around the corner into the bell mouth, it may need several screens or straighteners to make it smooth. The tunnel should also be placed far from things like walls, desks, or people, which can make the airflow uneven. If the tunnel is open to the air, wind and weather can also affect how the air moves.

The pressure is always less than atmospheric and so spurious jets issue from holes left unpatched, although this can be remedied by obstructing the tunnel outlet and creating an over- pressure in the working section [3].

The closed-circuit is another type of low-speed wind tunnel. A closed-circuit wind tunnel recirculates air in a closed loop, enabling precise control of airflow, temperature, and humidity while minimizing energy consumption and external influences.

Closed circuit wind tunnels (in FIG. 2) are important tools for advanced studies in aerodynamics and fluid flow. Their looped design helps keep the air conditions steady and reduces energy and pressure losses. This makes it easier to get accurate and repeatable test results.

The wind tunnel works as follows: A radial compressor unit, which is the main component, drives the flow [4]. The flow slows down in a wide-angle diffuser before entering the settling chamber. Turbulence screens are placed in the diffuser to prevent flow separation. Inside the settling chamber, there is a finned chiller. The chiller pipes are made of stainless steel due to pressure requirements, but aluminum fins are used to improve efficiency. The chiller provides the cooling needed to complete the thermodynamic cycle, which is an important factor in controlling the system as shown in FIG.3.

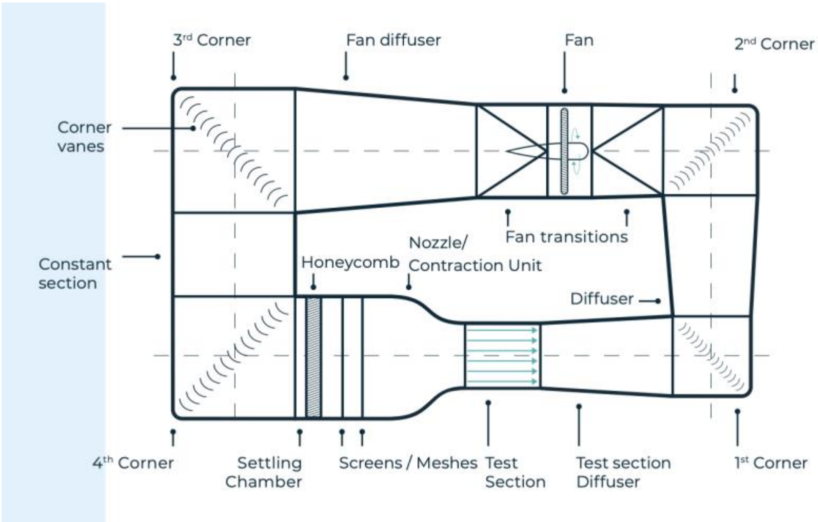

Figure 2. Closed circuit wind tunnels from WTTECHCZ

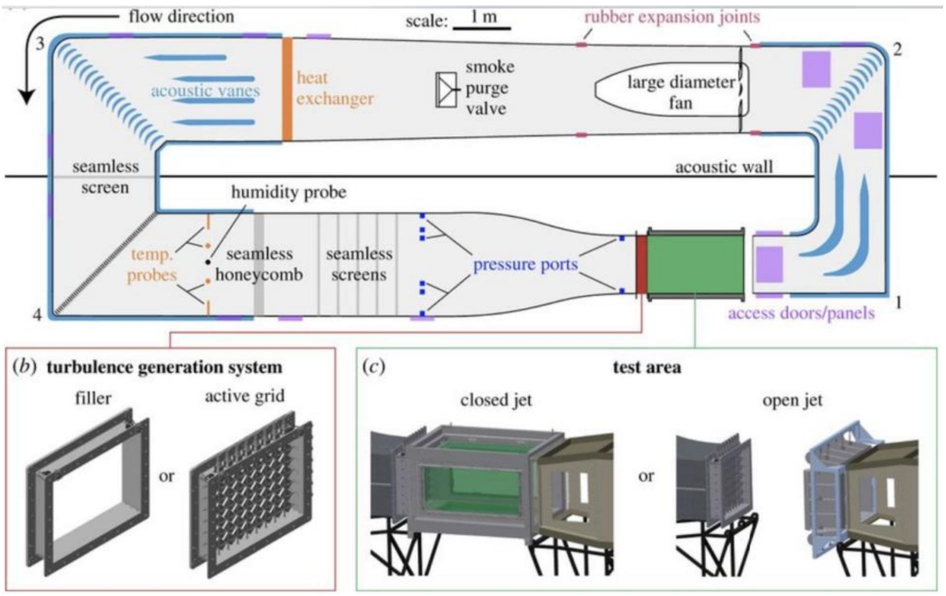

Figure 3. The operating principle of closed-circuit wind tunnel

After passing through a honeycomb and more turbulence screens, the flow slightly accelerates in the first contraction, which is made of three conical pieces, before entering the test section. For initial testing of the facility—checking for leaks, heating and cooling performance, pressure drops, and how well flow conditioners and the compressor work—a simple pipe is used.

The return section of the tunnel has a throttle valve that helps test the compressor at different loads. By measuring pressure, head, and mass flow with sensors and a Pitot tube, the real performance curves can be determined. These curves are necessary before finalizing the design of the test section, which is limited by the available power. The throttle valve can also be used to adjust the back pressure right after the test section, giving another way to control the operation.

Finally, the return of the tunnel connects to the compressor's suction side through an expansion joint to reduce side forces caused by thermal expansion of the heated pipes. The heating system, which uses heating cables, is divided into several thermally insulated zones to minimize heat loss to the environment.

2.2. Aeroacoustic Wind Tunnel

Aeroacoustics wind tunnel is a type of wind tunnel that measures the mechanisms of sound generation from bodies immersed under the flow environment of a wind tunnel with aerodynamic experiments in mind. The design of these different types of aeroacoustics wind tunnels all have to take into account a number of requirements and factors.

To accurately measure noise generation in this type of wind tunnel, two main acoustic conditions must be met. The first requirement is maintaining high-quality airflow in the test section. This is important because the airflow needs to remain smooth, uniform, and free from turbulence or disturbances that could affect sound measurements. In addition, the wind tunnel must be able to operate continuously and steadily at a wide range of wind speeds. This stability allows researchers to carry out long and precise tests, ensuring that both acoustic and flow data are consistent and reliable under different operating conditions. The turbulence intensity has to be kept very low and as a design goal which is a value less than 0.5%. The interaction of turbulence in the flow with the body will produce unwanted noise [5].

Additional design requirements include the ability to measure noise from airfoils and similar structures, the ability to operate steadily and continuously at the appropriate wind speed for extensive flow and acoustic measurements, the ability to measure frequencies higher than 500 Hz, and a low background noise sound pressure level [5].

In addition to these specifications, the background noise level must be significantly lower than the noise level being measured. Second, the test area must have distinct acoustic characteristics, such as being reverberant or almost anechoic. While some of the tunnels are open circuit tunnels, others have closed-circuit designs with closed or semi-closed test sections.

2.3. Subsonic Wind Tunnel

A subsonic wind tunnel is a device that generates a steady, controlled airflow below the speed of sound to study the aerodynamic forces and characteristics of models, typically for aircraft, cars, or buildings as shown in FIG.4.

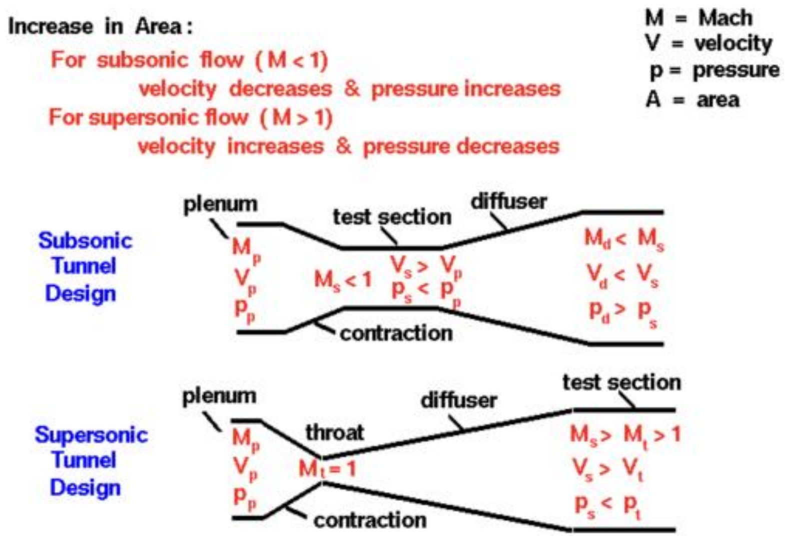

Figure 4. Factors considered in subsonic tunnel design and supersonic tunnel design

In a subsonic wind tunnel, the test section is located immediately after the contraction section and before the diffuser. Based on the principle of mass conservation for subsonic flow, the desired velocity or Mach number within the test section can be achieved by properly designing its cross-sectional area, since velocity is directly related to area variation. The figure illustrates how the Mach number, velocity, and pressure change throughout the wind tunnel. The plenum serves as the settling chamber in a closed-circuit tunnel, while in an open-circuit design it corresponds to the open room surrounding the test section.

In supersonic flows, air density within the tunnel varies significantly due to compressibility effects. The change in density occurs more rapidly than the change in velocity, by a factor proportional to the square of the Mach number. For such flows, a reduction in cross-sectional area leads to a decrease in velocity and an increase in pressure, while an expansion in area produces the opposite effect—

velocity increases and pressure decreases. These variations are the reverse of those observed in subsonic flow.

Compressible flows also exhibit the phenomenon of mass-flow choking. As a subsonic stream is compressed, both its velocity and Mach number rise until the speed of sound is reached (M = 1), at which point the flow becomes choked and cannot accelerate further. To achieve the maximum possible velocity in a supersonic wind tunnel, the flow is contracted until choking occurs at the nozzle throat, after which it expands through a diverging section to reach supersonic speeds. The test section of a supersonic tunnel is therefore located downstream of this diverging region. According to the conservation of mass for compressible flow, the desired velocity or Mach number in the test section can be obtained by appropriately designing the area ratio. The accompanying figure illustrates how Mach number, velocity, and pressure vary throughout the supersonic tunnel.

3. Structural Design Comparison and Technological Evolution

3.1. Topology Optimization

Topology optimization is a mathematical method that finds the most efficient material layout within a defined design space to maximize structural performance, such as stiffness, while minimizing material usage and weight. The method builds on repeated analysis and design update steps, mostly guided by gradient computation.

The general topology optimization problem is to find the material distribution that minimizes an objective function F, subject to a volume constraint $G_0 \leq 0$ and possibly M other constraints $G_i \leq 0, i = 1 \ldots M$ [6]. The basic problem can be solved in two ways. The first one is shape optimization [6]. It needs the possibility for making new holes so that it can be categorized as a topology optimization. The example of bubble-method by Eschenauer and co-workers [6]. The bubble-method is specifically called topological derivatives, which is a method under shape optimization. The second one is density approach. The level set approaches have the concept of operating with boundaries instead of local density variables. And we categorize the level set approaches that operate with ersatz material and fixed Eulerian meshes as the density approach.

3.2. Topography Optimization

Topography optimization is an advanced shape optimization technique used to automatically generate reinforcement patterns, such as beads and swages, on thin-walled structures to improve performance without increasing mass. It is particularly useful for maximizing component stiffness and natural frequency by manipulating surface geometry.

Compared to topology optimization, which removes material to create load paths, topography optimization adds material in the form of controlled surface reinforcements, creating optimized bead patterns that outperform traditional designs. And unlike traditional shape optimization, which only adjusts the size or dimensions of a given design, topology optimization allows engineers to add or remove material within a specific design space to achieve certain performance goals. These goals may include reducing weight, controlling temperature, preventing unwanted vibrations, or keeping stress and deformation within safe limits. Through this method, engineers can let the object’s performance guide the best distribution of material for an efficient and effective design.

3.3. Size Optimization

Size optimization is a method used to adjust the dimensions of structural parts in order to create an efficient design. Its main goal is often to reduce weight or cost while ensuring that the structure still meets performance limits such as allowable stress or displacement. This process focuses on improving parameters like material thickness, mechanical properties, or orientation angles, making it widely applied in areas such as transportation and renewable energy for producing lightweight and reliable designs.

Free-size optimization, on the other hand, is commonly used to improve machine parts, stamped or welded components, and especially complex laminated composite structures. In this approach, engineers define a continuous thickness distribution for each fiber direction so that the design can meet performance requirements. Afterward, more detailed refinement is carried out through ply bundle sizing optimization, where each bundle represents several plies of identical orientation and shape, with attention to detailed mechanical limits such as ply failure. The process concludes with *stacking sequence optimization*, which arranges individual layers to satisfy manufacturing rules while maintaining the best structural performance.

When early design analyses reveal high stress concentrations, engineers may apply shape or free-shape optimization to reduce the risk of failure. Shape optimization improves an existing geometry by adjusting certain dimensions—like height, length, or radius—to spread stress more evenly throughout the part. Free-shape optimization allows even greater flexibility, as designers can specify regions for stress reduction, and the software automatically generates an improved geometry for those areas. However, this flexibility comes at a cost, since free-shape optimization may not preserve small geometric details such as fillets or fine edges.

4. Methodology and Experimental Approaches

4.1. Traditional Experiment Approach

Flow visualization is a tool in experimental fluid mechanics that renders certain properties of a flow field directly accessible to visual perception [7].

Since it is a useful tool in fluid mechanics, fluid flow can be interpreted in various ways through different flow patterns, which can be visualized using methods such as dye or smoke injection into the flow field, or long-exposure photographs of seeded particles. So, what exactly is a *flow pattern*?

A flow pattern described by streamlines consists if special points where the streamline slope is indeterminant and the velocity is zero [8]. The points are called stationary point. By knowing the type of such points and their distribution, much of the remaining flow field and its geometry and topology can be deduced.

Hydrogen bubble visualization has greatly facilitated the fundamental understanding of a wide variety of fluid dynamic phenomena, including boundary layers, turbulence, separated flows, and wakes, to mention but a few [9].

The hydrogen bubble method visualizes water flow by producing very small hydrogen bubbles along a thin conductive wire (around 25–50 μm thick) that serves as one electrode in a DC circuit. The other electrode, typically made of metal or carbon, is positioned farther away in the water. When the wire functions as the negative electrode, electrolysis generates hydrogen bubbles on its surface, which are then carried downstream by the flow. Because the bubbles are extremely small—about half the wire's diameter—they closely follow the motion of the water rather than rising independently.

This technique is effective because the hydrogen bubble probe can be placed almost anywhere and at any orientation within the flow, causing minimal disturbance to it. It is also easy to build and low-cost, allowing experiments to be conducted quickly with simple equipment. However, its main limitation is that it performs best in water flows with relatively low Reynolds numbers.

In a similar way, airflow can be visualized by introducing smoke into the system. The smoke moves along with the air, making the flow pattern visible. A commonly used approach to generate this smoke is the smoke-wire method.

4.2. Modern Measurement Approach

Over the past thirty years, particle image velocimetry (PIV) has become a widely used technique in experimental fluid mechanics. Its main advantage lies in its ability to capture the instantaneous velocity field at many points simultaneously—typically between 10^3 and 10^5—with enough spatial resolution to calculate the instantaneous vorticity and strain rate of the fluid.

So far, PIV remains the only experimental method capable of providing such detailed information in rapidly changing flows [10]. Traditionally, PIV has been used to obtain snapshots of two- or three-component velocity vectors on a plane within the flow. However, recent advances have enabled PIV to measure velocity fields within entire volumes and to record time-resolved sequences, allowing researchers to track how the flow evolves over time as shown in FIG.5.

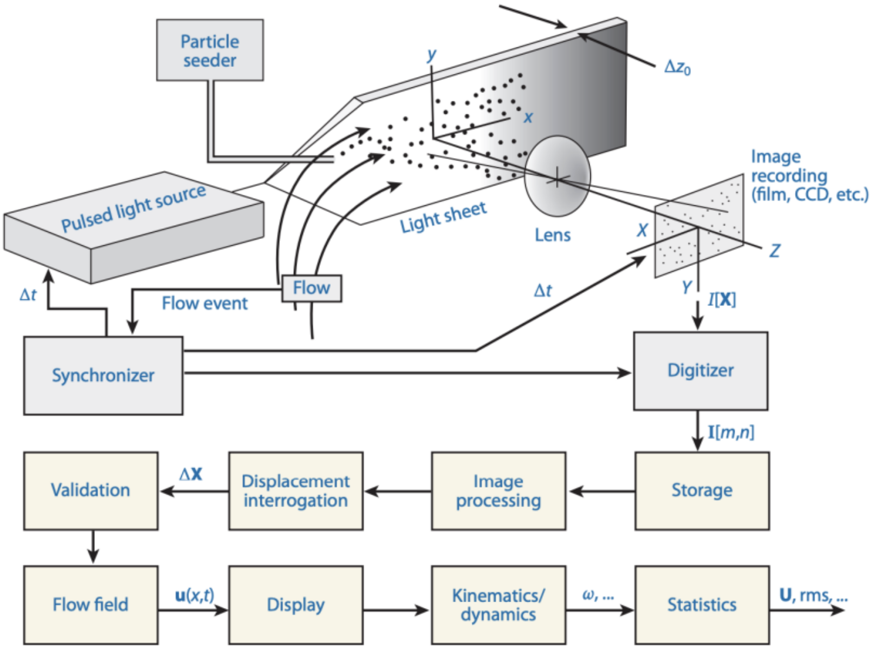

Figure 5. The procedure of PIV

LDAs are installed in areas where the terrain or other obstacles make it impossible to align the localizer antenna directly with the runway centerline. A Localizer Directional Aid (LDA) approach uses the same equipment as a regular localizer, and its course width is generally similar, though it can vary depending on local terrain and obstacle conditions.

4.3. Computational Fluid Dynamics

Over the past 30 years, computational fluid dynamics (CFD) has advanced significantly. Today, a wide range of commercial software is available, allowing almost anyone to perform complex flow simulations even on personal computers [11]. Looking back at the development of CFD, several groundbreaking milestones can be identified. In the aerospace field, CFD first gained major attention during the 1970s for its ability to simulate transonic flow.

4.4. Scaling Laws

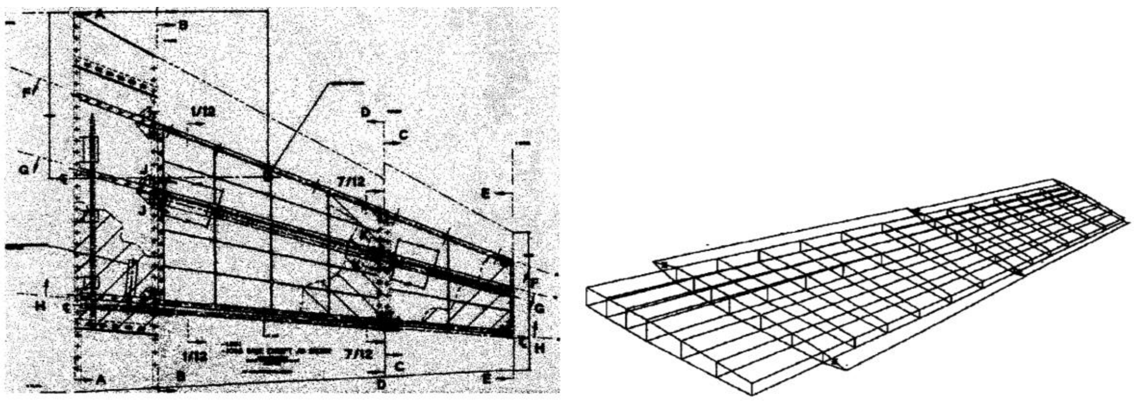

Figure 6. Detailed Layout of Wind Tunnel Model & Finite Element Model of Smart Wing

Several factors influence the choice of wind tunnel model scale, including the tunnel's dimensions and the cost of model fabrication. For the smart wing models, the achievable actuation forces played a major role in determining the appropriate scale as shown in FIG.6.

Another key design decision was whether the model should be dynamically scaled or only geometrically scaled. A dynamically scaled model would replicate the behavior of the full-scale aircraft, including its natural frequencies and flutter speed.

Once the model scale is determined, the preliminary design process begins. Starting from the outer mold lines (OML), the internal structural layout is then developed to support stress, dynamic, and aeroelastic analyses.

5. Application

5.1. Aerospace

In aerospace, a wind tunnel is a crucial experimental facility that creates a controlled stream of air to test scale models of aircraft and spacecraft and determine their aerodynamic performance. By simulating conditions an aircraft experiences in flight, engineers can measure lift, drag, and stability to ensure safety, improve fuel efficiency, and develop innovative designs before full-scale production. Data collected in wind tunnels informs decisions about aerodynamic shape, control systems, and structural design, ultimately leading to advancements in aviation.

A fan circulates air through a closed-circuit tunnel. Testing Section: The air is then directed into a test section, where a scale model of an aircraft or spacecraft is placed. Data Collection: Sophisticated instruments measure forces, pressures, and moments on the model. Visualization: Techniques like introducing smoke or applying fluorescent oil to the model's surface help visualize airflow patterns. Analysis: The collected data helps engineers understand how the air interacts with the design and how it will perform in real-world flight.

5.2. Cars and High-Speed Trains

Wind tunnel testing for high-speed trains and cars serves a similar purpose: to simulate real-world aerodynamic conditions and optimize vehicle design for factors like drag, stability, and noise. However, testing differs, with cars typically undergoing tests with both stationary and moving ground simulation. For trains, testing must also account for the complexity of the surrounding environment, such as tunnels, crosswinds, and different ground scenarios like embankments and viaducts.

A total of 22 typical detached and apartment houses from major Japanese cities were selected as case study areas for the wind tunnel experiments (Table 1). The selection was based on the range of gross building coverage and gross floor area ratio. Among them, Cases 1–15 represent detached houses, mostly one- or two-storey wooden structures, while Cases 16–22 represent apartment houses. Each case covers an area of 270 m × 270 m, typically part of a large housing estate. The local wind conditions were assumed to reflect general urban environments.

In the experiments, the vertical profile of the approaching mean wind speed followed a 1/4 power law, and the turbulence intensity was set to about 25% (at a real-scale height of 30 m), achieved using roughness elements (FIG.7). Since the study primarily focused on building density as a parameter, features such as trees and roof shapes were not included in the models.

As seen in FIG.8, roughly 50 measurement points were dispersed equally outside the buildings to cover each region. At a real-scale height of 1.5 m (or 5 mm in the wind tunnel), wind velocities were measured with a thermistor anemometer probe (AS201-7, Shibaura Electronics), which directly measures scalar velocity. The sensors have a maximum inaccuracy of 3% of the observed value and a full-scale measurement range of 20 m/s. Wind velocities were recorded simultaneously at several locations using a multi-channel measurement system (F6203H, Shibaura Electronics), with independent calibration for each sensor.

For the measurements, a sampling duration of 30 seconds and a frequency of 10 Hz were used. At each measurement site, these sampling parameters were thought to be adequate for obtaining a consistent average of the scalar wind velocity [12].

5.3. Environment and Buildings

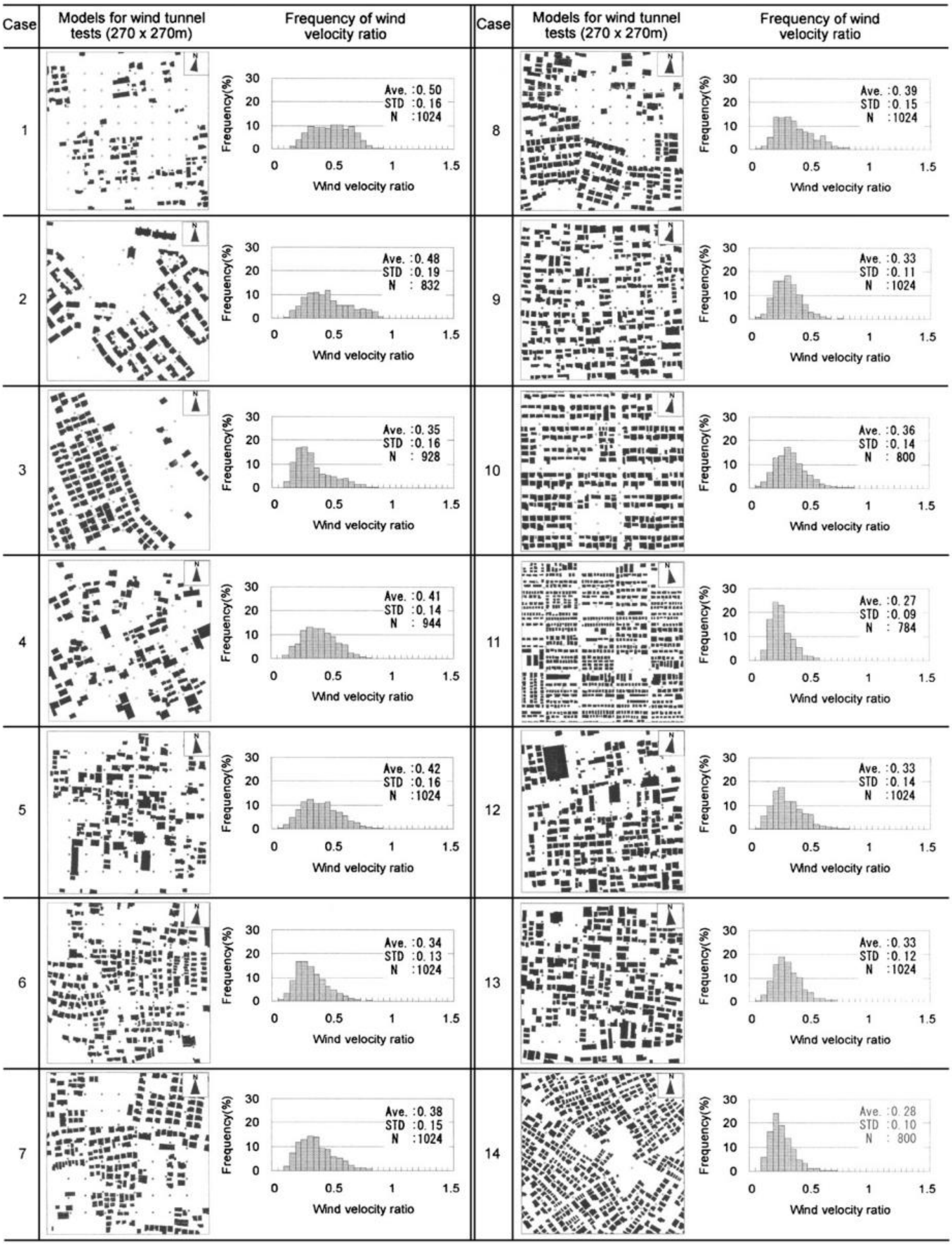

Figure 7. Data about the relationship between environment and building and the wind velocity collected using wind tunnels

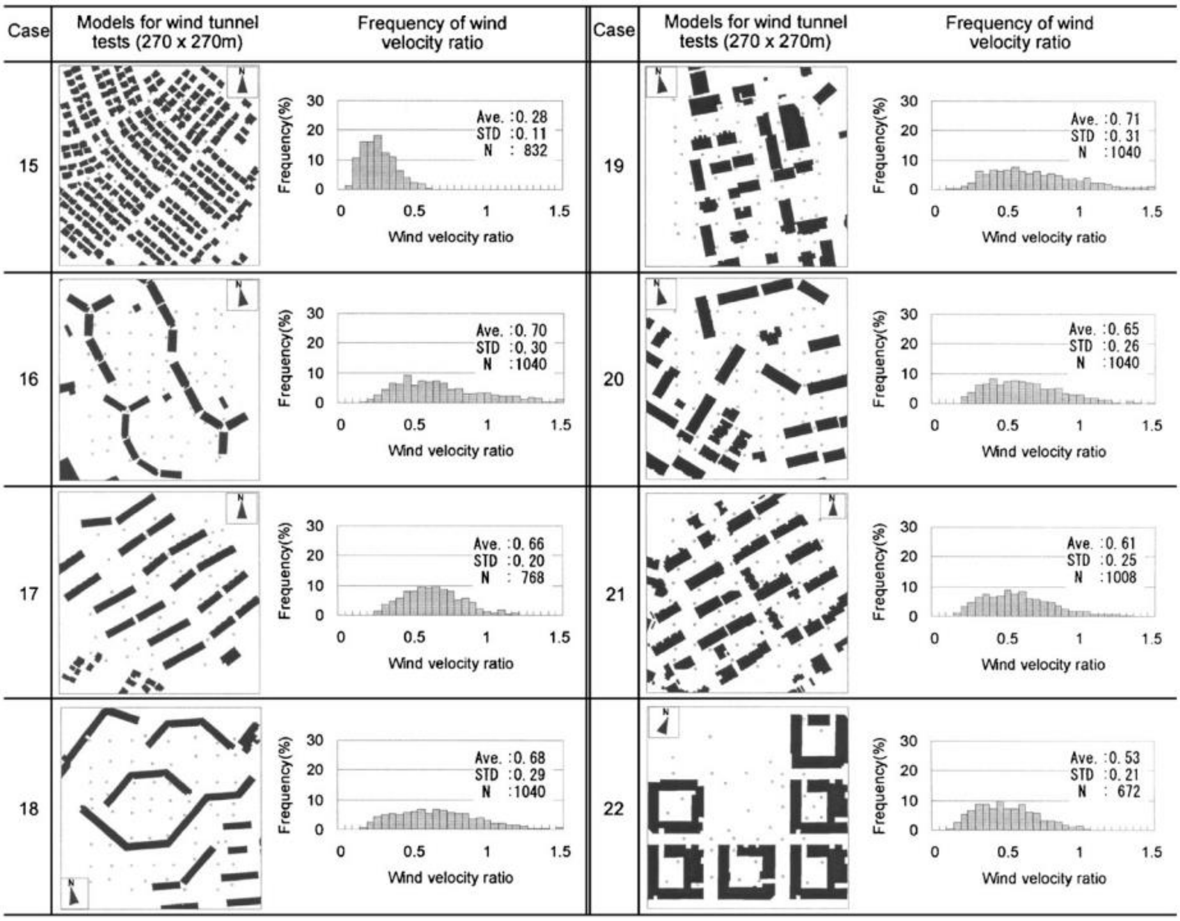

Figure 8. Data about the relationship between environment and building and the wind velocity collected using wind tunnels

6. Current Challenges and Development Trends

As the demands on aerodynamic performance, acoustic precision, and structural response continue to grow across aerospace, wind energy, transportation, and environmental science, wind tunnel technology is facing several key challenges while rapidly evolving toward intelligent, multidisciplinary, and digitally integrated systems.

6.1. Low Turbulence Intensity and High-Precision Acoustic Measurements

One of the foremost challenges in acoustic wind tunnel testing lies in achieving sufficiently low turbulence intensity (TI) and background noise levels. Even a turbulence intensity of less than 0.1% can introduce spurious vortex shedding or boundary-layer instabilities that obscure weak acoustic signals. Background noise from drive fans, structural vibrations, and wall reflections further complicates measurements.

To address this, specialized small-scale low-turbulence acoustic wind tunnels have been developed, emphasizing nozzle design, entrance flow conditioning with grids or screens, wall materials with acoustic absorption, and echo/noise suppression techniques. Recent studies report systematic characterization of turbulence levels and background noise in such facilities. However, replicating similar low-noise and low-turbulence conditions at high-speed, transonic, or supersonic regimes remains extremely difficult due to nozzle heating/cooling, wall roughness, and density effects.

6.1.1. Large-Scale Testing and Scaling Laws in Reduced Models

A second fundamental challenge arises from similitude constraints when scaled models are tested. Geometric scaling typically reduces model size, making it nearly impossible to simultaneously match

Reynolds number, Mach number, boundary layer characteristics, and structural flexibility. This mismatch leads to distortions in separation points, vortex shedding frequencies, acoustic spectra, and aeroelastic responses such as flutter.

Recent advances attempt to mitigate scaling problems through hybrid aeroelastic simulations, where physical wind tunnel models are coupled with numerical simulations via adaptive control systems (e.g., extended Kalman filters). These systems allow dynamic correction of structural response during tests. Other approaches include using high-pressure or variable-density facilities, substituting gases to increase Reynolds numbers, or designing flexible/morphing models with material stiffness tuned to preserve dynamic similarity.

Despite these developments, fully achieving similitude across multiple physical domains—fluid, acoustic, structural, and thermal—remains out of reach. Thus, integrating experimental data with numerical models for error quantification and uncertainty estimation is becoming essential.

6.2. Integration with Numerical Simulation and Digital Twins

The convergence of CFD and wind tunnel testing is now standard practice. CFD methods (RANS, LES, DNS) provide detailed insights into turbulence structures and boundary layer development, which in turn inform wind tunnel design and interpretation. Conversely, wind tunnel data validate and calibrate numerical models.

Digital twin concepts are extending this synergy by enabling real-time or near-real-time coupling of physical tests and simulations. For example, real-time aeroelastic hybrid simulations combine physical models with computational structural dynamics, updated through algorithms such as Kalman filters, to improve the fidelity of experiments.

Artificial intelligence (AI) and machine learning (ML) methods are increasingly used to optimize experimental design, automate active flow control strategies, calibrate sensors, and accelerate data processing. Examples include intelligent algorithms for aerodynamic parameter calibration and active learning strategies for flow control.

Challenges remain in ensuring reliability: discrepancies between simulations and experiments due to boundary conditions or turbulence modeling, computational costs of high-fidelity simulations, real-time system latency, and robustness of closed-loop control. Uncertainty quantification and data-driven model correction are key frontiers.

6.3. Future Intelligent and Multidisciplinary Wind Tunnels

The future of wind tunnels lies in greater **intelligence** and broader **multidisciplinary**. Intelligent wind tunnels will employ distributed sensor networks, real-time data analytics, AI-driven optimization, and adaptive control to regulate inflow, apply active flow control, or even morph test models dynamically. Examples already exist in experiments where neuro-fuzzy controllers mitigate aeroelastic vibrations in turbulent flows.

From the disciplinary perspective, wind tunnels are no longer restricted to classical aerodynamic testing. They are increasingly used for: Aerospace: lift/drag, noise, aeroelasticity. Wind energy: turbine blade design and optimization. Civil/structural engineering: building/bridge wind loads, urban ventilation, pollutant dispersion. Environmental science: climate simulation, air quality, noise propagation biological sciences: insect and bird flight aerodynamics.

Large-scale facilities like the Wendee Dome allow full-scale urban and environmental flow simulations, while advances in 3D printing and composite materials enable more realistic, deformable models. Variable-density, variable-pressure, or cryogenic tunnels further expand the achievable Reynolds and Mach number regimes.

Virtual/augmented reality (VR/AR) integration, cloud-based data sharing, and standardized turbulence/noise metrics will also contribute to more reproducible, collaborative, and efficient use of wind tunnel data.

7. Conclusion

Wind tunnels remain indispensable for probing aerodynamic, acoustic, and structural phenomena, offering controlled environments for physical validation. Over decades, they have evolved from simple force-measurement facilities into highly integrated experimental platforms capable of addressing Multiphysics interactions—acoustics, aeroelasticity, turbulence, and flow control.

Different design strategies are strongly interconnected with both experimental methodologies and application domains. For instance, low-turbulence wind tunnels directly enable precise acoustic testing, while large-scale/high-pressure facilities address similitude challenges. Numerical simulation and digital twins act as bridges, correcting scaling errors and enhancing predictive power. Applications across aerospace, wind energy, civil engineering, and biology all converge on the need for reliable, high-fidelity flow and response measurements.

Looking ahead, several trajectories are clear: Automation and intelligence: AI-driven experimental optimization, adaptive flow control, and morphing models will redefine how tests are designed and executed. Digital integration: tighter feedback loops between simulations, experiments, and digital twins will accelerate design cycles and reduce costs. Expanded regimes: facilities capable of reaching higher Reynolds and Mach numbers, through variable-density or alternative gases, will allow more realistic replication of extreme conditions. Multidisciplinary scope: beyond aeronautics, wind tunnels will increasingly support environmental sustainability, noise reduction, and bio-inspired design. Standardization and data sharing: harmonized turbulence/noise metrics and cloud-based platforms will strengthen reproducibility and collaboration. In sum, the evolution of wind tunnels is not just technological but conceptual shifting from isolated experimental tools to intelligent, multidisciplinary, and digitally connected platforms central to future aerospace and environmental innovation.

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