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Advances in Experimental Aerodynamics for Mechanical Engineering Applications

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Abstract

Experimental aerodynamics is an essential aspect when it comes to investigating the properties of fluid flow, verifying computer simulations, and improving the performance of aerodynamics of mechanical engineering applications. This paper presents a review of new developments in wind tunnels, aerodynamic testing methods, optical diagnostic tools of flow, and experimental flow control methods. Modern technologies such as Particle Image Velocimetry (PIV), Laser Doppler Velocimetry (LDV), Pressure-Sensitive Paint (PSP), and Schlieren visualization are described together with their use in automotive engineering, wind energy, turbomachinery, HVAC systems, and unmanned aerial vehicles. Some of the challenges faced by today's experimental aerodynamics and future trends are also considered. Thus, this review shows that advanced experimental methods are crucial for aerodynamic research and will further facilitate the development of efficient and sustainable mechanical engineering systems.

Keywords

Experimental Aerodynamics, Wind Tunnel Testing, Flow Visualization, Particle Image Velocimetry, Aerodynamic Flow Control

1. Introduction

In modern mechanical engineering, aerodynamics is the science that describes the fluid-body interaction process. An accurate prediction and control of aerodynamic forces have a direct impact on engineering systems' performance, stability, efficiency, safety, and environmental friendliness in applications including automobiles, wind turbines, turbomachinery, UAVs, heat exchangers, and HVAC equipment [1]-[4]. During the last century, many groundbreaking achievements in experimental aerodynamics allowed to deepen the knowledge about the complex flow phenomena and to develop optimal solutions.

The field of experimental aerodynamics has been originated in the end of nineteenth and the beginning of the twentieth centuries together with the creation of the wind tunnel test facilities that have made possible for researchers to conduct controlled experiments in the field of aerodynamics [5]. At first, the studies were mainly based on simple measurement procedures such as pressure measurements and visualization with smoke. The further advancement of instrumentation technologies has led to the appearance of many advanced measuring devices and techniques like hot-wire anemometry, Laser Doppler Velocimetry (LDV), Particle Image Velocimetry (PIV), pressure-sensitive paint (PSP), Schlieren visualization, and infrared thermography that have greatly increased the spatiotemporal resolution of experimental investigations [6]-[10]. Nowadays, the combination of all these advancements allows carrying out an experimental investigation of various complex phenomena such as turbulence, vortices, boundary layer processes, shock waves, and unsteady phenomena. Although there has been a great breakthrough in computational fluid dynamics (CFD) and numerical modeling, experimental aerodynamics is still very relevant for the validation of numerical models and the improvement of engineering predictions [11]-[13]. It is necessary to understand that even the most sophisticated CFD models contain some assumptions about turbulence modeling, boundary conditions, numerical discretization, and mesh resolution, and therefore there will always be some uncertainties in the obtained results. That is why, accurate and reliable measurements are still required for model verification, calibration, and uncertainty quantification.

The current level of advancement in optical diagnostics and non-invasive measurement techniques has brought about a revolution in experimental aerodynamics. Time-resolved PIV, tomographic PIV, high-speed digital imaging, advanced pressure-sensitive coatings, and laser diagnostic techniques now provide high-resolution and time-resolved 3D measurements of the complex flows [6] [9] [10]. At the same time, advancements in sensors technologies, high-speed data acquisition systems, image processing software, and automation of experimental setup have greatly increased the efficiency and repeatability of measurements. Recently, the artificial intelligence (AI) and machine learning (ML) have been used for intelligent image processing and flow-field reconstruction, as well as uncertainty estimation, feature extraction, and real-time experimental optimization [14] [15].

The need for energy-efficient transportation, renewable energy systems, sustainable building technologies, and aerospace applications has further underlined the relevance of experimental aerodynamics for mechanical engineering. In the automotive industry, experimental methods help to improve the aerodynamics of vehicles, reduce drag, increase stability, manage heat dissipation, and maintain passenger comfort. In wind energy, experimental studies help optimize the blades, characterize the flow field behind a turbine, and enhance the performance of wind turbines. Experiments in turbomachinery, HVAC systems, electronic cooling, sports engineering, biomedical devices, and bio-inspiration are crucial due to their complicated aerodynamic nature [1] [3] [4] [16]. Thus, experimental aerodynamics goes far beyond aerospace engineering and becomes a multidisciplinary research area relevant to many fields of mechanical engineering. There are still a number of problems limiting the scope of experimental investigations despite all advancements of the last decades. Among them, high cost of installing and operating the latest wind tunnels, scale effect, repeatability, optical access, and growing complexity of high-Reynolds and compressible flows are listed [8] [12]. Besides, constant advancements in digital twin technology, autonomous experimentation, robotics, and AI-assisted data collection may change experimental methodology in aerodynamics, giving new opportunities for fast and accurate aerodynamic investigations. The above factors are expected to have considerable influence on the future of experimental aerodynamics.

Figure 1 depicts the historical evolution of experimental aerodynamics starting from basic experiments in wind tunnel up to the present days with intelligent and autonomous experimental systems. The initial stages of development were focused on fundamental research related to force measurements and visualizations of flow fields, then moved to more complicated pressure and force measurements, as well as hot wire anemometry. Introduction of non-contact laser methods such as Laser Doppler Velocimetry (LDV) and Particle Image Velocimetry (PIV) contributed to increased accuracy of complex flow field measurements. Further improvements include optical measurement methods, high speed imaging, time resolved PIV and three-dimensional flows measurements. The latest developments in the field include artificial intelligence, automation and digital twins in experimental aerodynamics studies. Expected future directions include autonomous wind tunnels, artificial intelligence in experiments, closed loop experiments and sustainability of experimental facilities.

The current paper reviews the latest advances made in experimental aerodynamics and its application in mechanical engineering. It is not restricted to prior reviews covering computational aerodynamics, models of turbulence, and other aspects but rather focuses on the general context of recent advances and their applications, specifically in the field of experimental aerodynamics. The unique aspect of this review is that it provides an evaluation of the current state of flow diagnostics, including PIV, LDV, PSP, Schlieren imaging, smart sensing, high-speed measurements, together with AI/ML assisted analysis, combination of experimental methods with CFD, as well as flow control. Moreover, the current paper contrasts the mentioned advances from different perspectives of engineering practice and considers them in the context of automotive aerodynamics, wind energy, turbomachinery, HVAC, thermal management, and UAVs.

Sources for the present literature review were retrieved by conducting systematic literature searches using reputable scientific databases, namely Scopus, Web of Science, ScienceDirect, and Google Scholar. The search keywords included combinations such as "experimental aerodynamics", "wind tunnel testing", "particle image velocimetry", "laser Doppler velocimetry", "pressure-sensitive paint", "flow visualization", "aerodynamic flow control", and "applications of experimental aerodynamics". All peer-reviewed journals, review papers, monographs, and other technical sources related to the experimental approaches used in mechanical engineering were taken into account. The resulting set of sources was classified according to the following themes: aerodynamic basics, experimental facilities and methods, recent diagnostics developments, flow control, and mechanical engineering applications. The rest of the paper is structured as follows. The basic principles of experimental aerodynamics are described in Section 2. Wind tunnel facilities and modern experimental measurement techniques are presented in Section 3. Section 4 covers recent developments in experimental aerodynamics diagnostics and instrumentation. Flow control approaches are discussed in Section 5. Applications in mechanical engineering are reviewed in Section 6. Challenges and new technologies as well as future directions for research are covered in Section 7.

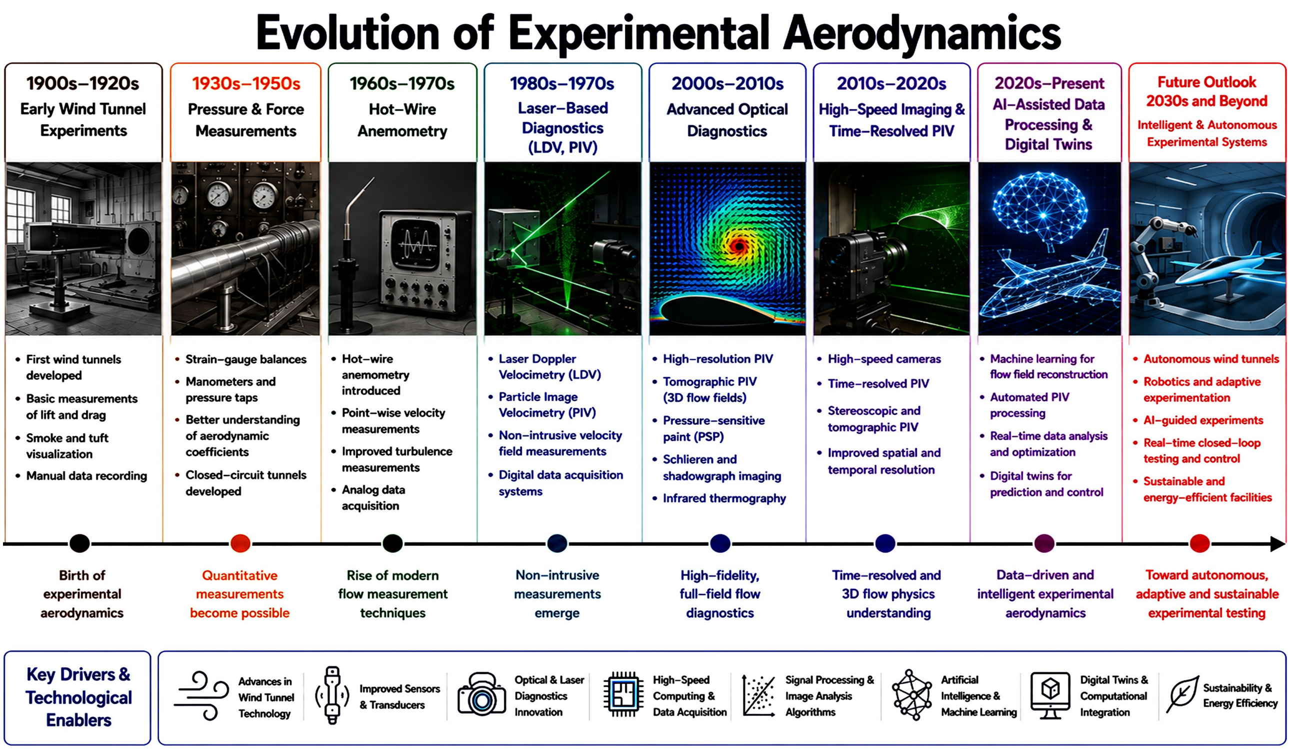

Figure 1. Evolution of experimental aerodynamics from classical wind tunnel experiments to modern AI-assisted aerodynamic testing.

2. Fundamentals of Experimental Aerodynamics

Aerodynamic experimentation is a scientific basis for the study of fluid dynamics in relation to engineering structures through experimental investigation in the laboratory. Even though numerical analysis has advanced over time, experimentation is still an essential tool for verifying computer calculations, studying flow characteristics, and creating reference data for engineering design. It is important to have adequate knowledge about the basic aerodynamic principles prior to learning about the new methods of experimentation and instrumentation. These principles include the fundamental equations of motion, dynamic similarity, boundary layer formation, flow separation, and aerodynamic force production, all of which determine the design of aerodynamic experiments [2]-[4] [17].

2.1. Governing Principles of Aerodynamic Flow

Flow behavior in aerodynamics is controlled by the principle of conservation of mass, momentum, and energy. In practical applications concerning the flow of air at low speeds, the fluid can be considered to behave like a continuum, meaning that its movement can be modeled using Navier-Stokes equations [3] [4]. This implies that the velocity, pressure, density, and temperature vary continuously.

The continuity equation expresses conservation of mass,

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \boldsymbol{V}) = 0, \tag{2.1}$$

where ρ is the fluid density and $\boldsymbol{V}$ is the velocity vector. The momentum equation relates pressure, viscous forces, and external body forces acting on the fluid,

$$\rho\left(\frac{\partial \boldsymbol{V}}{\partial t} + \boldsymbol{V} \cdot \nabla \boldsymbol{V}\right) = -\nabla p + \mu \nabla^2 \boldsymbol{V} + \rho \boldsymbol{g}, \tag{2.2}$$

where p represents the pressure and μ is the dynamic viscosity. The above governing equations provide the theoretical framework used in the interpretation of the experimental data obtained by using pressure probes, force balances, hot-wire anemometer, LDV, and PIV techniques [7]-[9].

Based on the Reynolds number value, an aerodynamic flow can either be laminar or turbulent. Laminar flows involve smooth flow of the fluid with low mixing, while the turbulent flows involve high irregularities of velocity values over various scales both in time and space. Due to the high Reynolds numbers in practical applications, turbulence is the key parameter that determines the aerodynamic characteristics [3] [17].

2.2. Reynolds Number and Dynamic Similarity

One of the most fundamental parameters in experimental aerodynamics is the Reynolds number,

$$\mathrm{Re} = \frac{\rho U L}{\mu}, \tag{2.3}$$

where U is the characteristic velocity and L is the characteristic length. The Reynolds number is used to find the proportionality between inertial forces and viscous forces and is one of the main factors influencing the transition from laminar flow regime to a turbulent one.

For experimental studies, the scaled model is often used instead of full-size prototypes. In order to make sure that the measured aerodynamic characteristics will be close enough to full-size prototype ones, dynamic similarity must be maintained in any case. It is based on the geometric similarity, kinematic similarity and dynamic similarity, the Reynolds number and Mach number being the most important similarity parameters in case of incompressible and compressible flows, respectively [2] [4]. Proper choice of scaling parameters allows reproducing real aerodynamic processes and making wind tunnel experiments cheaper and smaller. Therefore, similarity analysis becomes the foundation of experimental aerodynamics [4] [16].

Even though Reynolds number and Mach number are the main similarity criteria, they may not always suffice to cover all the relevant full-scale aerodynamics conditions. The tunnel testing data can be influenced by such factors as blockage ratio, freestream turbulence level, surface roughness, as well as reduced frequency for unsteady flows. Therefore, these parameters should also be taken into account in assessing the transferability of test data.

2.3. Boundary Layer Development

Since it was first presented by Prandtl in 1904, the boundary layer has become one of the fundamental phenomena in fluid dynamics and experimental aerodynamics [3]. When a fluid flows over the surface of a body, the effects of viscosity result in the creation of a thin layer near the surface where the velocity varies from zero at the wall to the value in the free stream. This layer is referred to as the boundary layer and affects such physical processes as drag, heat transfer, flow separation, etc.

The formation of the boundary layer starts as laminar but eventually becomes turbulent due to the growing influence of disturbances with increasing distance downstream or increasing Reynolds number. The boundary layer in a turbulent state is characterized by more momentum at the wall level and thus is more resistant to adverse pressure gradients than a laminar layer; this causes separation delay even though skin-friction drag is higher in this case [3] [18]. Experimental studies of the boundary layer characteristics typically use such methods as hot-wire anemometry, laser Doppler velocimetry, particle image velocimetry, oil-flow visualization, and pressure measurement [7]-[9].

2.4. Flow Separation and Wake Formation

Flow separation happens in a situation where the kinetic energy of the boundary layer fluid becomes insufficient to resist the adverse pressure gradient such that the near wall flow starts reversing its direction and separates from the surface [2] [3]. The separation results in a recirculation region whose features include steep velocity gradients, turbulence, vortices and pressure drop. Separation strongly affects lift, drag, aerodynamic noise, vibration, and fatigue induced by the flow. While bluff bodies have large separations, streamlined shapes are purposely designed to avoid separation [1] [2] [10] [19].

It is thus among the major reasons why the understanding of flow separation is a main aim in experimental aerodynamics. The recent developments in optical diagnostics, especially PIV and Schlieren visualization, have made it possible for scientists to visualize flow structures resulting from vortex shedding and turbulent mixing [8] [9].

2.5. Lift, Drag, and Aerodynamic Performance Parameters

The aerodynamic characteristics of an engineering component are generally measured by lift force and drag force. Lift acts normal to the flow direction, and drag acts tangential to the incoming flow. They are mostly presented in terms of lift and drag coefficients,

$$C_L = \frac{L}{\frac{1}{2}\rho U^2 A}, \tag{2.4}$$

$$C_D = \frac{D}{\frac{1}{2}\rho U^2 A}, \tag{2.5}$$

where L and D denote lift and drag forces, respectively, and A represents the reference area.

Pressure distribution over the body surface is frequently represented by the pressure coefficient,

$$C_p = \frac{p - p_\infty}{\frac{1}{2}\rho U^2} \tag{2.6}$$

This is quite useful in understanding the loading and flow dynamics. In experimental testing, the lift, drag, and pressure coefficients are measured by means of force balances, pressure taps, pressure transducers, and pressure sensitive paints [7] [8]. The above-mentioned parameters are among the main criteria for aerodynamic design and optimization of various machines such as vehicles, airplanes, windmills, turbomachines and others. The basic physical laws stated in the above section provide the necessary theoretical background to understand the modern methods of experiments. The following section will give a review of modern wind tunnels, test equipment and diagnostic methods to characterize the aerodynamic flows in engineering applications. **Figure 2** shows the basic aerodynamic effects that determine the external flow behavior around an airfoil. Pressure effects over the surface of the airfoil result in generation of lift and pressure drag (**Figure 2(A)**), and the aerodynamic force acting on the airfoil could be divided into lift and drag components in relation to the free stream (**Figure 2(B)**). **Figure 2** also shows how the boundary layer separation and wake develop at increasing angles of attack up to stall conditions, when there is a change from attached flow to large-scale flow separation (**Figure 2(C)**). These aerodynamic flow effects serve as the starting point for aerodynamic experiments and are often measured using force measurements, pressure measurements, and flow diagnostics methods such as PIV, LDV, and Schlieren photography [2] [3].

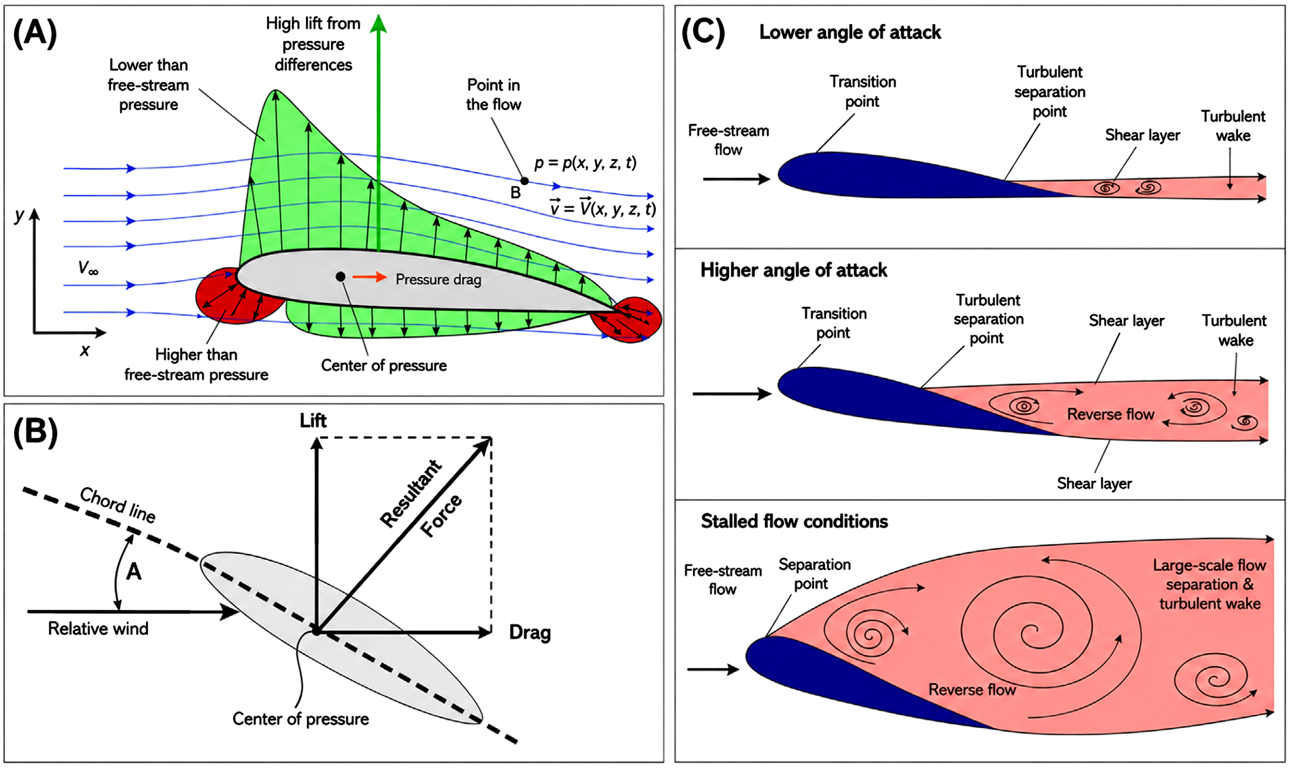

Figure 2. Fundamental aerodynamic phenomena investigated in experimental aerodynamics [2] [3].

3. Experimental Facilities and Measurement Techniques

Aerodynamics through experiments is an approach that involves precise tests carried out in well-defined surroundings and accurate methods of measuring in order to explore the behavior of the flow of fluids surrounding engineering parts. The wind tunnel technique ensures the creation of precise flow surroundings to carry out an assessment of the aerodynamic performance under defined operating conditions, whereas the modern instruments make it possible to carry out precise measurements of velocity, pressure, force, temperature, and the flow structure. Advanced measurement technologies have been developed in the field of optical diagnosis, fast photography, and digitization of data [3] [7] [9] [20].

3.1. Wind Tunnel Facilities

The wide popularity of wind tunnels is associated with the ability to provide controllable flow regime of working fluid. According to the type of circulation, wind tunnels are usually divided into open-circuit and closed-circuit designs. Open-circuit wind tunnels use air from the atmosphere as the working fluid and discharge it into the environment; therefore, they are cheaper and are used mostly for educational purposes and low-speed aerodynamics researches. On the other hand, the design of closed-circuit wind tunnels provides continuous circulation of the working fluid and ensures higher uniformity of flow, low turbulence, and decreased operating costs and environmental impact [2] [3].

There are several types of wind tunnels depending on the operational speed, such as low-speed, transonic, supersonic and hypersonic tunnels. The low-speed wind tunnels are widely applied for investigation of aerodynamics of automobiles, HVAC systems, sports engineering and wind energy, while the high-speed wind tunnels are used mostly for aerospace researches. Modern wind tunnels include various flow conditioning devices, contraction section, test section, diffusers and control system ensuring high-quality flow [2] [20].

3.2. Force and Pressure Measurements

Identification of aerodynamic forces and pressure distributions is one of the main purposes of experimental aerodynamics. Measurement of aerodynamic forces is usually accomplished through multi-component force balances that are able to determine lift, drag, side force, and pitching moment very precisely. Current strain-gauge force balances are very accurate across a large spectrum of loadings and are used in the majority of research wind tunnels [21].

Measurements of pressure distribution on the model surface are performed through pressure taps connected to the differential pressure transducer or electronic pressure scanner. In recent years, an interesting non-invasive technique, called Pressure Sensitive Paint (PSP), has become a highly developed tool allowing measurement of pressure field on the surface with very good resolution [22].

3.3. Velocity Measurement Techniques

The precise determination of velocities is necessary to understand the behavior of aerodynamic flow and validate computational models. The Pitot-static probe continues to be one of the simplest and commonly used devices for mean velocity measurement by applying Bernoulli’s principle. Inexpensive and reliable though it is, its use is restricted only to steady flow and pointwise velocity determination [4]. The hot-wire anemometry (HWA) is capable of high-frequency velocity fluctuation measurements and has been extensively used in turbulence research due to its high temporal resolution. However, this method is intrusive and needs proper calibration [9].

The Laser Doppler Velocimetry (LDV) measures the fluid velocity by observing the Doppler shift of scattered laser light by the tracer particles. As it is a non-intrusive optical technique, it offers accurate measurements of velocities and thus is used extensively to investigate turbulence flows, rotating machinery, and boundary layer formation [8]. The Particle Image Velocimetry (PIV) is undoubtedly one of the greatest achievements in experimental aerodynamics. Different from pointwise measurement methods, PIV measures the velocity field in a plane or volumetrically using tracer particles in laser sheets in an instantaneous manner. Modern time-resolved and tomographic PIV systems allow for a detailed study of vortices, wakes, and turbulent flow dynamics [7] [8].

3.4. Optical Flow Diagnostics

Optical diagnosis has been a revolutionary advance in experimental aerodynamics in terms of making it possible to study complicated flow phenomena without any interference. Schlieren and shadowgraphs are popular tools in the study of compressible flows, shock waves, thermal plumes, and density stratifications, since they are based on refractivity of transparent fluids [20]. Infrared thermography is now widely used for studying the surface temperature distributions and detecting the boundary layer transition based on heat transfer features. In a similar way, LIF (laser-induced fluorescence) and PTV (particle-tracking velocimetry) can be used for studying the flow scalar transport and mixing features [9] [20]. The use of fast digital cameras in connection with optical diagnostics has greatly enhanced the possibilities of contemporary aerodynamic laboratories, since they made it possible to observe the transient flow phenomena visually.

3.5. Data Acquisition and Uncertainty Analysis

Accurate experimental measurements demand reliable data acquisition systems along with uncertainty analysis. Contemporary aerodynamic testing rigs are equipped with high-speed digital data acquisition systems which allow to measure simultaneously multiple data streams from force transducers, pressure transducers, velocity probes and optical equipment. The growing power of computational systems makes possible the synchronization of the data acquisition process, image processing and experiment automation [20].

Uncertainty of measurements results from the inaccuracy of measuring equipment, calibration, disturbances of the environment, signal noise and experiment repeatability. Nowadays international recommendations such as ASME Verification and Validation (V&V) standards stress the importance of systematic uncertainty estimation to assure the reliability of experimental data and their usage in the process of verification of computational models [11]. Uncertainty analysis became an integral part of modern experimental aerodynamics. Modernization of experimental facilities, optical diagnostics and digital measuring techniques made significant contribution into enhancement of possibilities of aerodynamic research laboratories. These developments provide the possibility of measurements of complex flow features and strengthen the connection between experimental studies and CFD. Below is presented the review of modern technological achievements changing the scope of experimental aerodynamics and making it applicable to mechanical engineering.

The structure of a modern-day experimental facility used for aerodynamic studies is depicted in **Figure 3**, where an open-loop wind tunnel is used. The device has several units such as flow conditioning section, settling chamber, contraction section, test section, diffuser, and fan, which together create uniform and controlled airflow. In the test section, force balances, pressure transducers, laser-optical diagnostics system, and digitized data acquisition systems are mounted to allow aerodynamic forces and pressure, velocities, and flow structures measurements. This combination of components leads to obtaining of high quality data for aerodynamic studies and visualization and modeling of flows in various fields of mechanical engineering [2] [7] [20].

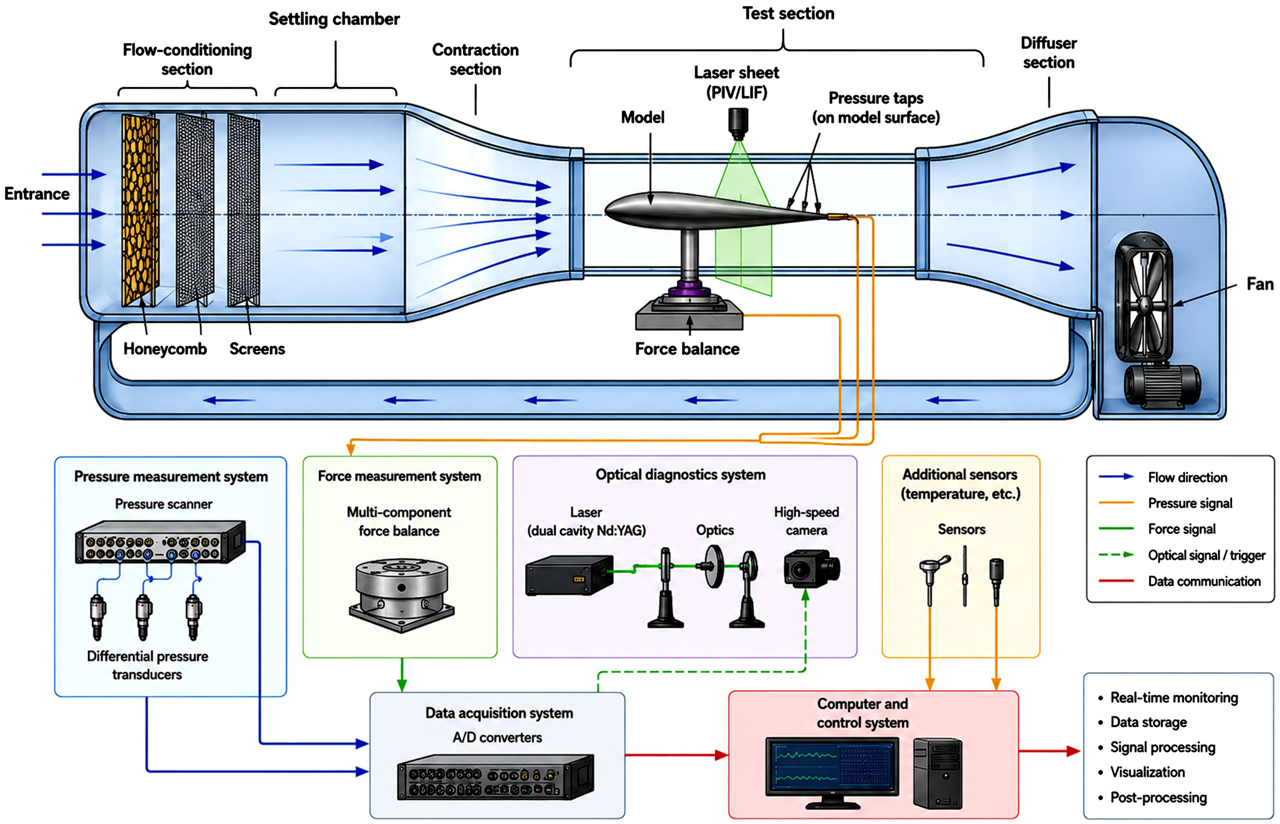

Figure 3. A schematic diagram of a modern experimental aerodynamics laboratory which indicates the major elements of a closed loop wind tunnel. The figure includes the contraction, settling, test, diffuser sections, fan, flow conditioning apparatus, force balance, pressure measurement system, laser based optical diagnostic system, and the digital data acquisition system [2] [7] [20].

Table 1 shows a comparative discussion on the current experimental aerodynamic measurement techniques available according to the type of physical quantity being measured, their main advantages, disadvantages, and engineering applications. Traditional methods like Pitot-static probes and hot wire anemometers provide accurate point-wise velocity measurements, while optical techniques like Laser Doppler Velocimetry (LDV) and Particle Image Velocimetry (PIV) allow non-invasive and highly detailed visualization of flow fields. Pressure-sensitive paints allow for the full-field measurement of surface pressure, and Schlieren visualization is useful in visualizing density discontinuities and shock wave formations in compressible flow. This discussion highlights the complementarity between these techniques and helps in choosing proper experimental techniques based on the aerodynamic study requirements.

The choice of an experimental diagnosis method is determined mainly by the necessary spatial and temporal resolution and constraints posed by the testing facilities. Hot wire anemometry (HWA) offers high temporal resolution, but it is invasive and gives localized flow data. Laser Doppler velocimetry (LDV) offers non-invasive velocity measurements at a certain point and good temporal resolution, but it requires optical access and proper alignment. Particle image velocimetry (PIV) allows obtaining spatially-resolved velocity fields and is very convenient for studying complex flow phenomena, though the accuracy of such measurements greatly depends on the quality of seeding, illumination, image resolution, and calibration. Pressure sensitive paint (PSP) allows non-invasive surface pressure mapping, but it also requires optical access and proper calibration and may be affected by temperature and illumination conditions. The Schlieren technique is highly efficient for qualitative analysis of density distribution, especially in compressible flows, but it cannot measure velocities and pressures directly. Therefore, the correct measurement technique should be chosen taking into account the required measurement resolution, intrusiveness, optical access, calibration complexity, and uncertainty.

Table 1. Comparison of commonly used experimental aerodynamic measurement techniques.

Technique	Measured Quantity	Advantages	Limitations	Typical Applications
Pitot-static tube	Mean velocity	Simple, inexpensive	Point measurement	Wind tunnels, HVAC
Hot-wire anemometry	Velocity fluctuations	Excellent temporal resolution	Intrusive, fragile	Turbulence studies
LDV	Velocity	Non-intrusive, accurate	Complex alignment	Boundary layers, turbomachinery
PIV	Full-field velocity	High spatial resolution	Expensive equipment	Wake flows, vortices
Pressure-sensitive paint	Surface pressure	Full-field measurement	Temperature sensitive	Aircraft, automotive
Schlieren imaging	Density gradients	Visualizes shock waves	Qualitative in many cases	Compressible flows

4. Recent Advances in Experimental Aerodynamics

4.1. Advances in Optical Flow Diagnostics

In recent years, there have been advancements in optical diagnostic techniques capable of performing non-invasive, full-field imaging of complicated aerodynamic flows. Among the various techniques, PIV is currently the most popular experimental technique due to the capability of instantaneous mapping of full field velocity vector fields. Advanced techniques such as stereo-PIV, tomographic PIV, and time-resolved PIV have advanced the traditional 2-D analysis by providing 3-D and transient analyses of vortex structures, turbulent structures and flow separation phenomena [7]-[9] [23].

The LDV technique still gives high accuracy in point wise velocity and is especially useful in turbulence analysis and CFD validation. More recent advances in volumetric measuring techniques, and hybrid optical diagnostics which combines PIV with LIF have allowed the simultaneous analysis of velocity and scalar transport [7] [8].

4.2. High-Speed Imaging and Non-Intrusive Measurements

High-speed cameras, pulsed laser techniques, and data acquisition systems have revolutionized aerodynamic experiments by allowing time-resolved visualizations of rapidly changing flows. High speed photography is widely used to study vortex shedding, shock wave interactions, dynamic stall, aeroacoustics, and transient wakes [9] [24]. Pressure sensitive paint (PSP) has seen great advancements in the last decade. Contemporary PSP technology allows for high resolution, full-field, non-intrusive surface pressure measurements that make them especially well-suited for complicated three-dimensional configurations. Temperature sensitive paint (TSP) has become increasingly useful in studies of aerodynamic heating and transition of the boundary layer in aerospace applications [22] [25].

4.3. Smart Sensors and Advanced Instrumentation

Integration of micro-electro-mechanical system (MEMS), fiber optic sensing techniques, small-scale pressure sensors, and wireless sensors has brought about considerable improvement in the experimental methods used. Sensors have provided increased sensitivity and response rates, as well as less interference in the measurement process [26]. Advances in distributed sensing have allowed for the collection of pressure, temperature, force, and vibration information from several points in complicated aerodynamic models. Together with high speed digital data acquisition systems, these sensing systems make it possible to measure multiple parameters concurrently and increase the reliability of aerodynamic tests [7] [26].

4.4. Artificial Intelligence in Experimental Aerodynamics

Artificial Intelligence and Machine Learning are rapidly revolutionizing experimental aerodynamics with automation in the field of image processing, feature extraction, and experimental optimization. Deep learning is being extensively employed for particle identification in PIV images, reconstruction of flow fields, denoising of images, and detection of vortices, significantly cutting down post-processing times with improved accuracy of measurements [14] [15]. Machine learning is being applied along with Digital Image Correlation, Pressure Sensitive Paint, and High Speed Imaging techniques to design experiments intelligently and monitor the aerodynamics in real time. Moreover, data fusion using AI is helping in combining measurements from different diagnostic tools to study complex aerodynamic phenomena [14] [27].

However, despite these strengths, any flow field reconstruction and denoising using AI and ML methods should be independently validated before making any qualitative conclusions. The effectiveness of the model highly depends on the type of the flow, the training data used, the seeding process, imaging parameters, as well as the experiment itself. Hence, an AI/ML model trained for one experiment might not work for another.

4.5. Integration with Computational Aerodynamics

Current developments increasingly focus on the convergence of experimental aerodynamics and CFD. Instead of working independently, current studies in aerodynamics use experimental data for verification of the models, testing the turbulence models, quantifying the uncertainty, and improving the numerical simulations [11]. Digital twin technology represents one of the main developments in this area through the combination of experimental data, sensor data, and CFD simulations to create continuously updated virtual models. This approach enables predictive analysis, monitoring, and adaptive optimization of the aerodynamic processes in different fields of mechanical engineering [27] [28].

The further development of optical diagnostic tools, intelligent instruments, fast camera technology, artificial intelligence, and digital twin technologies allows increasing the capabilities of experimental aerodynamics in many ways. Besides improving the measurement process itself, it allows enhancing the convergence of experimental and computational modeling approaches. **Figure 4** gives examples of recent progress made in experimental aerodynamics diagnostics methods. Contemporary optical measurement methods such as Particle Image Velocimetry

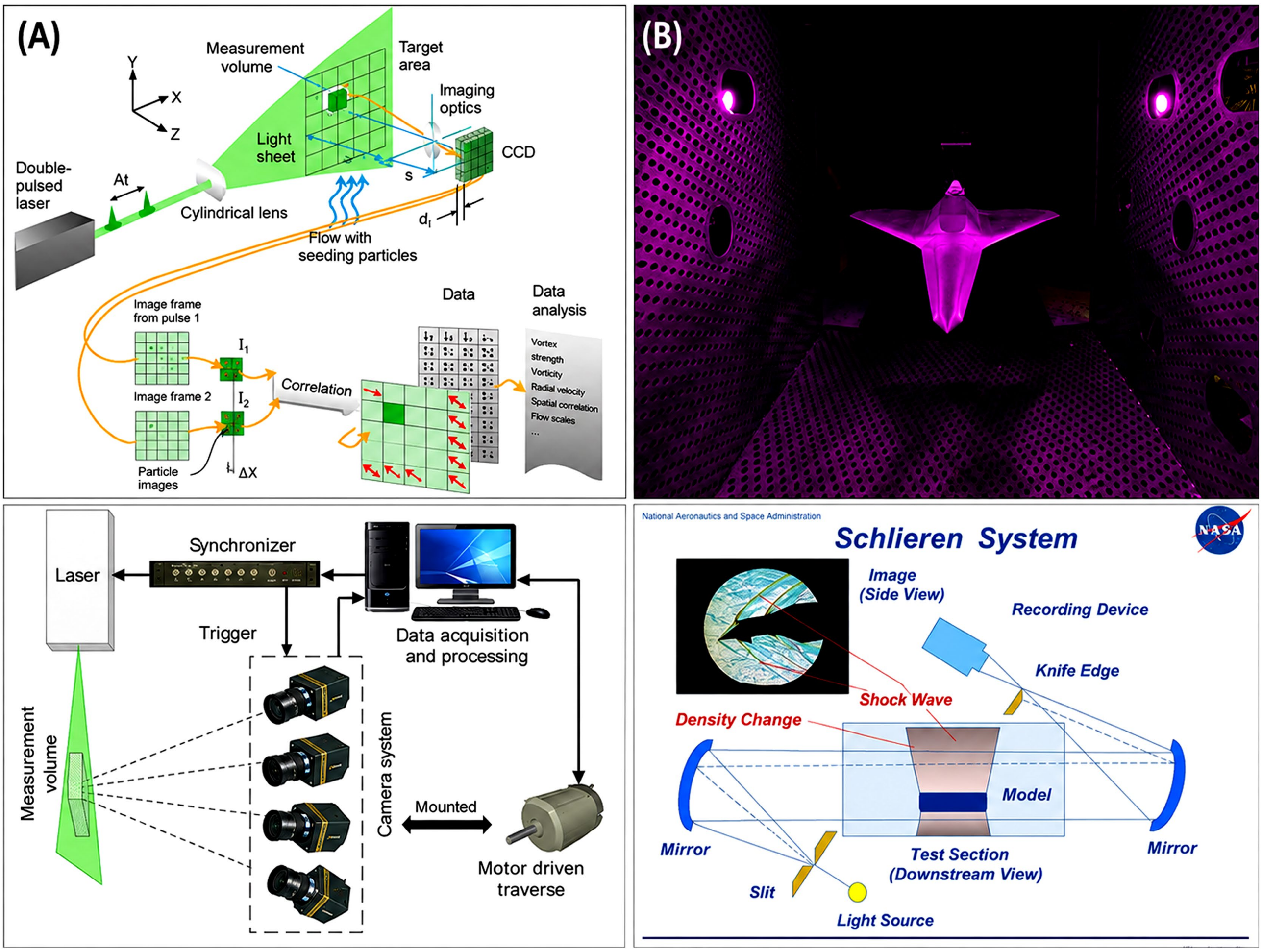

Figure 4. Advances in experimental aerodynamics diagnostics: (A) Working principle of Particle Image Velocimetry (PIV) technique, (B) Pressure-Sensitive Paint (PSP) on a model in a wind tunnel, (C) Typical configuration for conducting experiments with PIV, and (D) Schlieren imaging apparatus [8] [9] [22] [25].

(PIV), Pressure-Sensitive Paint (PSP) and Schlieren imaging enable to measure velocity field, pressure distribution at surfaces and features of compressible flows without interference. The use of synchronization between measuring devices and the data processing systems has substantially enhanced the precision of experimental research in aerodynamics by making it possible to investigate turbulence, boundary layer formation, vortex processes and shock wave interaction [8] [9] [22].

5. Experimental Flow Control Techniques

Flow control has recently become one of the most promising topics in the field of experimental aerodynamics because of the great possibilities for enhancement of aerodynamic efficiency, reduction of drag, suppression of flow separation, increase in lift and reduction in aerodynamic noise. The main goal of the flow control is to manage the properties of the boundary layer and wake in order to obtain better flow properties under various conditions. It is especially important to conduct experimental studies of flow control due to the possibility of measuring the velocity and pressure fields, vortices and aerodynamic loads at realistic conditions [3] [9] [16] [19].

5.1. Passive Flow Control

Passive control techniques do not require external energy input to control the flow and hence, they are very attractive because of their simplicity, reliability, and low cost of operation. Passive flow control devices usually work by making changes to the geometry of the aerodynamic surface that influences the boundary layer and prevents the onset of flow separation [29] [30]. Of the different types of passive flow control devices that have been studied over time, vortex generators have been studied extensively. This is a flow control technique whereby small projections on the flow field create streamwise vortices that help transfer high momentum fluid to the wall in order to energize the boundary layer [29] [31].

There has also been increasing interest in bio-inspired flow control surfaces. Flow control surfaces that mimic the structure of shark skin, bird feathers, and humpback whale flippers have exhibited promising results in reducing skin friction drag and improving aerodynamic performance. PIV, PSP, and force balance studies have been conducted to understand how these flow control surfaces achieve improved aerodynamic performance [30].

5.2. Active Flow Control

In contrast to passive control devices, active control strategies need some form of energy supply to actively manipulate the flow structure. Active strategies offer much more flexibility since the magnitude of control can be regulated according to different operational parameters. Some common active techniques are synthetic jets, plasma actuators, steady and pulsed blowing and suction, oscillating excitations, surfaces in motion, and fluidic oscillators [3] [32]. One of the most researched active flow control techniques has been synthetic jets. They produce periodic vortex formation without a need for a constant mass flux. Numerous experiments have proven that synthetic jets are very effective at delaying separation, improving lift, and decreasing aerodynamic drag over a wide range of Reynolds numbers [33].

Another novel technology that has been proven successful for active aerodynamic flow control is Dielectric Barrier Discharge (DBD) plasma actuators. They produce localized body forces which increase the speed of the boundary layer flow and inhibit separation. The compactness, quick response time, and lack of mechanical parts make them an interesting technology for aerospace, automotive, and wind-energy industries [34]. Many experiments with the help of wind tunnels and PIV/Schlieren visualizations have been conducted to study their flow dynamics.

5.3. Experimental Evaluation of Flow-Control Performance

The efficiency of flow-control systems is examined with the help of experimental investigations of aerodynamic loads, pressure distributions, velocity fields, turbulence, and wakes. The force balance gives direct data about lift and drag coefficients, and pressure distribution around the body and/or control devices is obtained using pressure taps and pressure-sensitive paint technology [3] [9]. Optical methods such as Particle Image Velocimetry, Laser Doppler Velocimetry, and Schlieren technique are often used in experiments for investigation of flow physics. They give an opportunity to visualize the vortex formation, boundary-layer transition, flow separation, turbulent mixing, wake formation, and, therefore, understanding the physical principles of aerodynamic performance enhancement [7] [8]. Very recently, time-resolved PIV and tomographic PIV techniques allowed to investigate the flow structures in 3D domain due to the action of actuators. Further development in the experimental evaluation of flow-control techniques was achieved because of the progress in high-speed imaging and digital image processing. In particular, the application of artificial intelligence and machine learning algorithms to experiments improved the data analysis and optimization of actuator performance [15].

In conclusion, the experimental studies show that active and passive flow-control techniques can significantly improve aerodynamic performance depending on operational conditions and application area. Passive flow-control devices are more reliable and energy-efficient in comparison with active devices under fixed operational conditions. Active flow control allows reaching higher aerodynamic performance in a wide range of operational conditions. Development of optical diagnostics and automation of experiments will provide us with further insight into the flow-control technologies. **Figure 5** gives several examples of passive and active flow control techniques used in aerodynamic experiments. The use of passive flow control devices such as vortex generators, Gurney flaps, riblets, and biomimetic surfaces increases aerodynamic performance without any energy consumption, as shown in **Figure 5**. Nevertheless, as presented in **Figure 5**, the Dielectric Barrier Discharge (DBD) plasma actuator as an active flow control device uses the wall jet created by the actuator to energize the boundary layer and delay separation [19] [29] [31] [32] [34].

An improvement in aerodynamic performance is not necessarily equivalent to an overall system benefit, particularly for active flow control systems which require some form of energy input on a continual or intermittent basis. Consequently, such systems should be evaluated not only on the basis of their effect on lift, drag, separation, and pressure distributions but also on their power requirements, effective control regions, control effectiveness, and flow robustness.

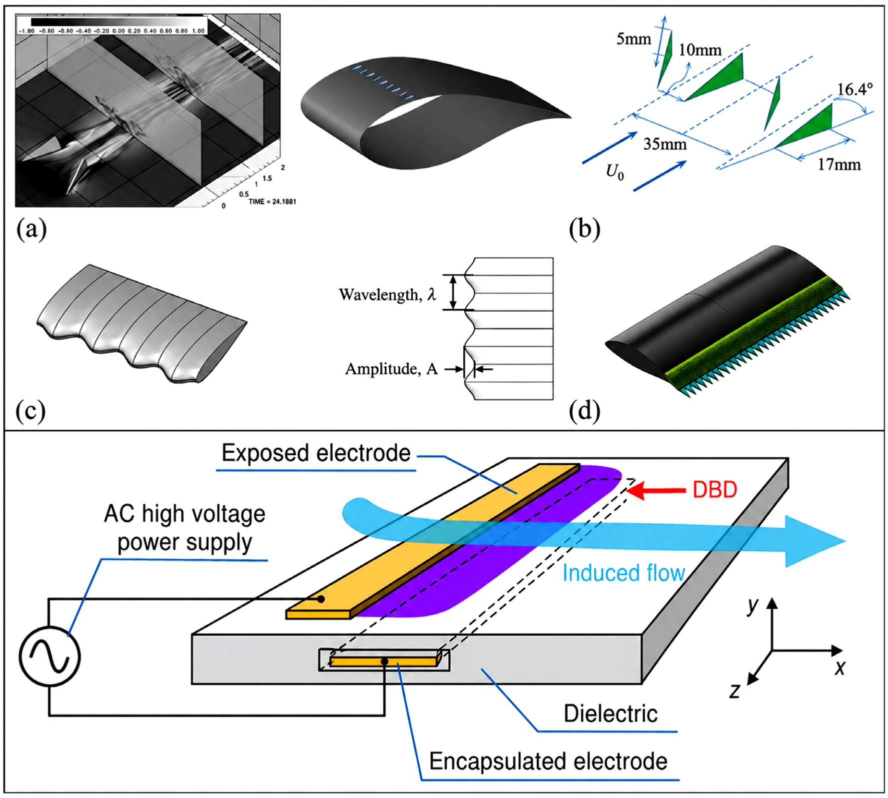

Figure 5. Examples of experimental flow control methods: (A) Some of the examples of passive flow control methods such as vortex generators, Gurney flaps, riblets, and biological inspired methods for boundary layer manipulation and drag reduction; (B) An illustration of the operation mechanism of the DBD plasma actuator which uses a wall jet for active boundary layer control [29]-[32] [34].

6. Mechanical Engineering Applications

Experimental aerodynamics is an indispensable tool in the process of designing and optimizing different mechanical engineering systems. Advancements in wind tunnel measurements, optical diagnosis, force measurements, and flow visualizations have made it possible to conduct research on the flow processes in realistic working conditions. Not only can experimental aerodynamics be used for validating the computational fluid dynamics calculations but also as a source of inspiration in developing novel aerodynamic designs. The scope of applications of experimental aerodynamics includes such fields as automotive engineering, renewable energy systems, turbomachinery, heat transfer, and UAVs [2] [3] [9] [16].

6.1. Automotive Aerodynamics

Aerodynamic drag is one of the major elements that determine the fuel efficiency, emission and speed stability of automobiles. It has therefore been through the experimental studies that the development of the stream-lined shapes of automobiles, as well as optimized under-body shapes, rear diffusers and spoilers, among others, has been achieved. Wind tunnel testing, when combined with force balances, pressure-sensitive paint (PSP) and Particle Image Velocimetry (PIV), makes possible the study of pressure distribution, wake behavior and vortex behavior around cars [35]. The recent development involves the use of moving ground systems and rotating wheel models in order to simulate actual road conditions, which improves the aerodynamic measurement significantly [36].

6.2. Wind Energy Systems

Aerodynamic experiments play an important part in improving the effectiveness and reliability of wind turbines that either belong to horizontal- or vertical-axis type. Wind tunnel and on-site tests are widely used for the study of aerodynamics of blades, dynamic stall, formation of blade tip vortexes, as well as turbine wakes. With the help of such optical diagnostics as stereo PIV and laser Doppler velocimetry (LDV), the visualization of blade tip vortexes and wake recovery allows optimizing blade shape and turbine spacing [37] [38]. Experimental investigations are also widely used in order to evaluate the effect of passive and active flow control devices on the wind turbine performance.

6.3. Turbomachinery

Compressors, turbines, pumps, and axial fans function under complex three-dimensional flow conditions, which have a considerable impact on the performance and stability of the equipment. The experimental aerodynamic approach provides researchers with an opportunity to conduct a thorough investigation of blade boundary layers, secondary flow, tip leakage vortices, and flow separation in rotating devices. High-speed particle image velocimetry (PIV), laser Doppler velocimetry (LDV), pressure testing, and hot-wire anemometry are commonly used to estimate velocity fields and turbulence in the blades of turbomachines [9] [39].

6.4. HVAC and Building Aerodynamics

The field of Heating, Ventilation and Air Conditioning (HVAC) is significantly dependent on aerodynamic optimization for the purposes of improving airflow distribution, thermal comfort inside buildings, and energy efficiency. The tools of wind tunnel tests and smoke visualization are often employed for studying airflow characteristics near the structures, ventilation ducts, and air distribution systems. The experimental research contributes to diffuser design optimization, ventilation performance, contaminant dispersion, and natural ventilation [40]. Similar approaches are widely used in urban aerodynamics for evaluating pedestrian wind environment and pollutants dispersion around buildings.

6.5. Heat Transfer and Electronic Cooling

Thermal management systems greatly benefit from experimental aerodynamics through increasing the convection heat transfer efficiency near the heat exchanger, electronics, batteries, and coolant passages. The combination of flow visualization technology with the infrared thermography, particle image velocimetry (PIV), and temperature-sensitive paint allows to measure simultaneously the fields of velocity and temperature, which helps to analyze the phenomena of fluid flow and heat transfer in a complex manner [41].

6.6. Unmanned Aerial Vehicles and Bio-Inspired Engineering

The explosive proliferation of UAV technology has resulted in comprehensive experimentation in areas such as low Reynolds number aerodynamics, interaction between propellers and wings, gust effects, and aerodynamic stability. Data obtained using force balances, PIV and pressure testing in wind tunnels are indispensable in improving design parameters of UAV wings and propulsion system [42]. On the other hand, various bio-inspired designs based on birds, insects, bats, and marine animals continue to attract considerable attention in relation to maneuvering capability and energy efficiency. Investigations into bio-mimetic wings and skin textures indicate promising results in lift creation, drag reduction, and flow control [30].

The area of experimental aerodynamics is still developing in line with the progress in sensor technologies, high-speed cameras, algorithms for AI processing, digital manufacturing, and others, thus extending its applications in mechanical engineering and improving experimental accuracy and efficiency. The increased involvement of the experimental approach in conjunction with the development of computational and intelligent data processing tools is expected to lead to more innovations in such areas as automotive engineering, renewable energy, turbomachinery, heat transfer, and UAV design. The next section discusses the future challenges and directions in the area of experimental aerodynamics.

Figure 6 shows some sample applications of experimental aerodynamics in major fields of mechanical engineering. **Figure 6(A)** presents an example of automotive aerodynamics experiments that aim at analyzing drag reduction, wake generation, and car stability. **Figure 6(B)** presents wind turbine aerodynamics by means of laser-based optical diagnostics of blade aerodynamics and wake structure. **Figure 6(C)** illustrates an example of experimental investigation of turbomachinery aimed at analyzing blade flow properties to increase aerodynamic efficiency. **Figure 6(D)** illustrates an example of airflow visualization for heating, ventilation, and air conditioning systems. In general, all these examples demonstrate the wide use of experimental aerodynamic techniques in performance evaluation, flow visualization, and design optimization [9] [35] [37]-[40].

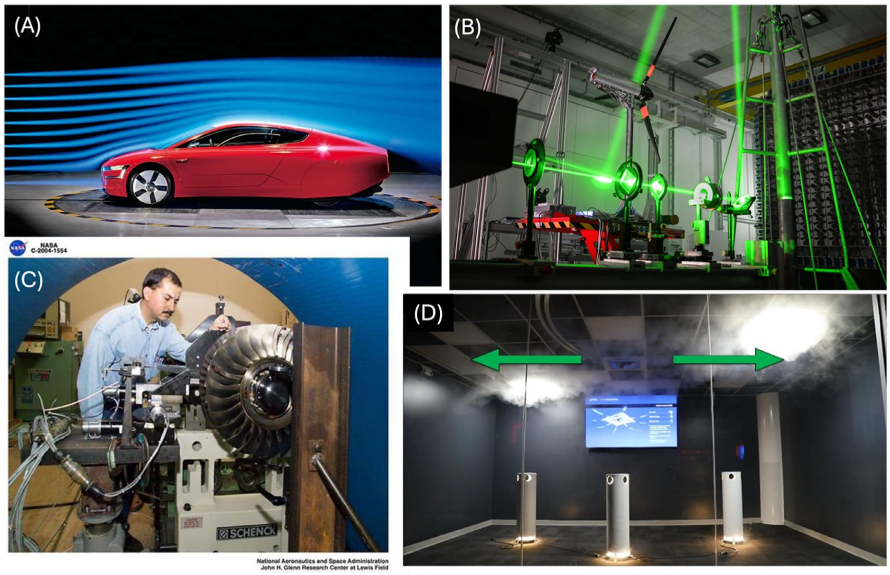

Figure 6. Sample aerodynamic experiments in mechanical engineering: (A) aerodynamics experiments on automobiles in wind tunnels, (B) experiments on the aerodynamics of wind turbines using optical techniques based on laser, (C) experimental study of turbomachinery aerodynamics, and (D) visualization of airflows for HVAC and indoor ventilation investigations. Such examples illustrate the application of modern experimental methods to evaluate aerodynamic performance and flows [9] [35] [37]-[40].

7. Challenges and Future Perspectives

Despite the tremendous advancements in the field of experimental aerodynamics, there still remain various scientific and technical issues that restrict the precision, effectiveness, and relevance of the experimental methods. Due to the increasing requirements for high-precision measurements and increasing complexity of the engineering structures, constant improvements are required in the areas of experimental setups, measuring instruments, data processing, and computer integration [2] [3] [9]. These issues must be solved in order to apply experimental aerodynamics to new mechanical engineering problems.

7.1. Current Challenges

One of the challenges that the field of experimental aerodynamics faces is that of carrying out precise measurements in the complicated flow fields. Turbulent effects, separated flow, transitional flow in boundary layers and compressibility effects lead to highly fluctuating flow fields both spatially and temporally thus making it difficult to make the accurate measurements. The recent advancements in optical measurement techniques such as Particle Image Velocimetry (PIV), Laser Doppler Velocimetry (LDV), and Pressure Sensitive Paint (PSP) have improved considerably the ability to measure accurately. Nevertheless, factors like optical accessibility, lasers alignment, distribution of tracers and resolution of the images affect the measurement error [7] [8] [24].

Another problem associated with experimental data is that of uncertainty of the experimental results. The reasons for uncertainty may be errors caused by sensor calibration, environmental conditions, manufacturing tolerance of the model used, data acquisition system and signal processing. Therefore, the need for uncertainty estimation, repeatability estimation and developing the unified experimental procedures becomes increasingly important in order to obtain the reliable experimental data, which can be used for the CFD simulations validation [11]. Another challenge is that of scaling. Since full-scale experiments cannot be done due to their impossibility, scaling is often used to reduce the expenses and the size of the experiment. However, complete dynamic similarity including both Reynolds and Mach number similarity may not always be achieved. Thus, scaling effects may cause errors in comparison between laboratory data and the reality, especially in high-speed aerospace application and wind power generation systems [2] [3].

The complexity of experimental facilities introduces another difficulty in terms of expenses, maintenance and data analysis. Modern aerodynamics laboratories need complicated laser systems, rapid recording, precise sensors and powerful computers thus making experiments complicated and expensive. In addition, advanced optical measurement techniques generate huge amount of data which has to be effectively processed using computer calculations [9] [24].

7.2. Future Perspectives

The potential future directions in experimental aerodynamics are supposed to be developed due to the improvements achieved in intelligent sensors, automation, and digitization. Artificial Intelligence (AI) and Machine Learning (ML) have proved themselves as effective tools for automatization of different operations, such as image processing, flow field reconstruction, uncertainty quantification, and experimental optimization. The use of deep learning together with optical diagnostics is likely to significantly reduce the time needed for data processing and improve the accuracy and reproducibility of experiments [14] [15]. Digital twins are regarded as one of the prospective directions of future aerodynamics researches. Due to the use of real-time measurement results, CFD, and sensors, digital twins allow for continuous monitoring and optimization of engineering systems. Thus, the mentioned hybrid computational-experimental approach will enhance the process of aerodynamic design and reduce the time and costs of testing in automotive, aerospace, and renewable energy industries [27].

Further development of sensor technologies is supposed to extend the list of possible future experiments. In particular, MEMS sensors, fiber-optic sensors, wireless measuring systems, and sensor networks are expected to provide increased spatial resolution and opportunity for multi-parameter measurements without perturbations of experiment. Along with autonomous data acquisition systems and positioning robots, the technologies mentioned above will enable researchers to conduct fully automated experiments without human participation.

The further development of optical diagnostics methods will contribute to even more enhanced opportunities in experimental aerodynamics. In particular, the innovative methods of volumetric PIV, tomographic PIV, holography, hyperspectral diagnostics, and high-speed 3D flow visualization will give additional insight into the structure of complicated flows and aerodynamic processes. The mentioned methods are expected to allow for deeper understanding of complex flow physics in hypersonic vehicles, wind turbines, turbomachinery, and microfluidics. Furthermore, sustainability will be one of the main concerns of future experiments. Namely, the construction of energy-efficient wind tunnels, green laboratories, and sustainable aerodynamic configurations will minimize the negative impact on the environment caused by experiments. Also, the increase in the usage of additive manufacturing technologies will enable the fast fabrication of complicated aerodynamic models; thus, accelerating the process of prototype development and experiments. In conclusion, the future of experimental aerodynamics will involve integration of novel measurement techniques, intelligent analysis, digital twins, and computational modeling. These aspects will make the aerodynamic experiments faster, more accurate, and automated, making it possible to create more efficient mechanical engineering systems. Collaboration between experimentalists, computational scientists, and data experts will be necessary in solving current issues in experimental aerodynamics.

8. Conclusions

Experimental aerodynamics can be considered one of the key areas of research in mechanical engineering, which offers effective ways to investigate aerodynamic flows and validate computer simulations. Thanks to ongoing developments in wind tunnel design, measurement tools, optical diagnostics, and flow visualization, we can now gain insight into the behavior of aerodynamic flows under real-life conditions. Recent achievements in experimental aerodynamics have played a significant role in understanding the nature of boundary layer formation, flow separation, turbulence, wakes, and generation of aerodynamic forces.

In this review, the latest developments in the field of experimental aerodynamic techniques have been discussed, which included modern methods of measurements, flow diagnostics, flow control experiments, and applications in automotive engineering, wind energy, turbomachinery, HVAC, thermal management, and UAVs. The critical importance of experimental studies for the enhancement of aerodynamic performance of systems was demonstrated. However, despite the great progress that has been achieved in the field, problems related to measurement uncertainty, scaling issues, expensive experimental costs, and data processing remain a motivation for future researches. The further advancements in the field are expected to include such topics as intelligent sensors, artificial intelligence, digital twins, autonomous experimentation, and optical flow diagnostics. Thus, the further advancement of experimental aerodynamics along with computation modeling and intelligent data processing will increase the significance of this field.

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Author Contributions

Conceptualization, A.M. and S.B.; methodology, A.M.; literature review and data collection, A.M.; formal analysis and interpretation, A.M. and S.B.; visualization and figure preparation, A.M.; writing—original draft preparation, A.M.; writing—review and editing, S.B.; supervision, S.B.; project administration, S.B. All authors have read and agreed to the published version of the manuscript.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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