Advancing Fluid Mechanics through Method Integration in Flow Studies

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Abstract. Flowing around objects is a fundamental subject in fluid mechanics, with wide relevance in both theoretical studies and engineering practice. Research in this area has been advanced through three principal approaches: analytical methods, wind tunnel experiments, and Computational Fluid Dynamics (CFD). Each of these approaches has its own strengths and weaknesses. Analytical methods are efficient and provide clear physical insight, but they are often unable to capture the complexity of real flows with sufficient accuracy. Wind tunnel experiments achieve the highest degree of accuracy and realism by directly observing flow behavior, yet they are limited by issues of scale, cost, and facility constraints. CFD has become a dominant tool in recent years because of its flexibility and broad applicability, but the accuracy of its predictions depends strongly on the choice of turbulence models, numerical schemes, and available computational resources. This review focuses on the integration of these methods rather than relying on any single one. Analytical approaches can provide theoretical foundations to guide the construction of CFD models. Wind tunnel data can then serve as benchmarks for validation. Through this combined strategy, the weaknesses of individual methods can be reduced, and the resulting framework can be applied to a wider range of flow problems with improved reliability and efficiency.

Keywords: Flow around objects, Analytical methods, Wind tunnel experiments, Computational Fluid Dynamics (CFD), Method integration.

1. Introduction

Studying fluid mechanics is important for many fields, including engineering and architecture. Achievements such as SpaceX's reusable rockets have made understanding fluid mechanics more significant than ever. Three main methods have driven its development.

Analytical methods form the foundation of fluid mechanics by providing a physics-based framework to predict flow behavior without costly experiments or simulations. By solving the Navier-Stokes equations under idealized assumptions, engineers can quickly estimate dimensions or approximate values of parameters. Recent work by Frolov et al. advances data-driven modal decomposition methods, such as Dynamic Mode Decomposition (DMD), to identify coherent structures in complex flows [1]. They applied DMD to unsteady flows over airfoils, capturing key features and quantifying flow characteristics. Analytical methods thus provide essential guidance for further studies.

Wind tunnel experiments remain the most effective way to obtain precise data. Guo et al. highlighted their importance in studying unsteady flows like vortex shedding and full-scale wind turbine aerodynamics [2]. By combining advanced PIV (Particle Image Velocimetry) with real-time data systems, the authors captured transient rotor dynamics that simulations cannot fully replicate. Their study explored how turbine performance changes under turbulent flows and ways to improve efficiency. Wind tunnel experiments are crucial because they provide real-world feedback, validating other methods.

Computational Fluid Dynamics (CFD) allows researchers to study airflow around irregular shapes. While wind tunnel experiments can also achieve this, CFD is less costly and more versatile. Zhang et al. demonstrated CFD's effectiveness in simulating wind-induced vibrations in high-rise buildings, showing it can replace expensive experiments while still providing accurate wind load predictions [3]. Using LES (Large Eddy Simulation) and RANS (Reynolds-Averaged Navier-Stokes) models, they simulated wind behavior in urban areas in detail. CFD is increasingly relied upon where experiments are impractical due to cost or scale, offering precise predictions and flexible applications.

In summary, analytical methods provide efficient early-stage design guidance. Wind tunnel experiments deliver high-fidelity data, capturing complex flow phenomena missed by theoretical or computational models, and can validate both analytical and CFD results. CFD offers scalable and accurate simulations of complex geometries. Combining these three methods gives a comprehensive understanding of fluid behavior, leading to optimized designs and faster innovation. The complementary use of these methods will continue to enhance the reliability and efficiency of aerodynamic systems across industries.

2. Methods

2.1. Analytical Method

Analytical methods form the backbone of aerodynamic research, providing a physics-based framework for interpreting flow behavior before conducting costly experiments or simulations. These methods originate from the Navier–Stokes equations, which express conservation of mass, momentum, and energy in viscous flows. By simplifying these equations under assumptions such as inviscid, incompressible, or steady-state conditions, researchers can obtain tractable solutions for velocity fields and pressure distributions. While such simplifications limit applicability in turbulent or strongly nonlinear flows, they remain indispensable as a first line of investigation.

Kumar et al. emphasize that theoretical analysis is not isolated but serves as the foundation for experiments and CFD simulations [4]. Their review shows that linearized potential flow theory provides quick, low-cost baseline predictions of lift and drag, particularly during early wing and engine design stages. Simplified models efficiently estimate parameters such as thrust ratio and bypass ratio at cruise conditions and identify flow regions prone to separation or strong vortices. However, as Kumar et al. note, these models tend to underpredict unsteady phenomena such as vortex shedding or wake interactions. For instance, RANS simulations predicted boundary layer separation with 10% uncertainty in engine mass flow rate and 0.05 uncertainty in Mach number at 0.25, highlighting the trade-off between accessibility and accuracy, which must be resolved via validation against higher-fidelity methods.

Wei, Huang, and Song proposed a rapid aerodynamic optimization method for flying wing aircraft during conceptual design [5]. Their framework combines surrogate modeling with the Vortex Lattice Method (VLM) and nonlinear programming to balance computational speed and accuracy. As shown in Fig. 1, VLM results were compared with NASA wind tunnel data, showing high efficiency: as the authors note, “the vortex lattice method … only takes a few seconds to calculate a state point,” whereas CFD requires significantly more computational resources. By using Latin square sampling and multi-island genetic algorithms to explore the design space, followed by local refinement via Quadratic Lagrangian (NLPQL) methods, the approach enables multiple design iterations at low cost.

The method’s effectiveness is demonstrated quantitatively as follows:

$$CD,i,opt = 0.0037 \approx 0.9CD,i,0 \tag{1}$$

The induced drag coefficient decreased by 10%, while the lift-to-drag ratio improved from 26.3 to 27.3. However, the authors note its limitations. Since VLM neglects viscous and compressibility effects, it cannot capture nonlinear separation or shock–vortex interactions, and surrogate model accuracy diminishes in highly nonlinear design spaces. Therefore, this analytical framework is most suitable for rapid early-stage exploration and requires CFD or wind tunnel validation for final design reliability.

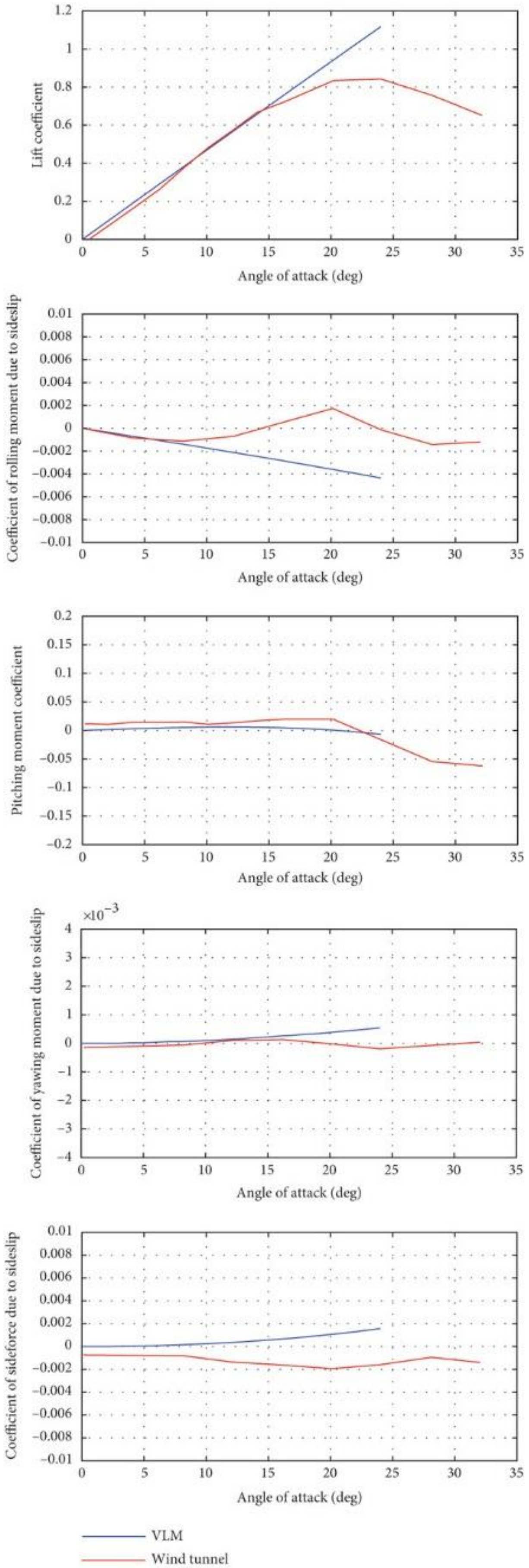

Figure 1. The comparison of aerodynamic derivatives of the flying wing aircraft calculated by the vortex lattice method and NASA's wind tunnel experiment results

To address some of these limitations, Liu et al. investigated vortex methods as an enhancement of classical theory, particularly for rotorcraft applications [6]. Unlike potential flow models that ignore unsteady wake dynamics, vortex methods explicitly capture trailing vortices and downstream interactions. This approach offers a compromise between overly simplified linearized theory and computationally intensive LES or DNS simulations. Liu et al. show that vortex methods predict wake-induced loads and aeroelastic instabilities more accurately than traditional methods while still demanding less computational effort than full CFD. Nonetheless, challenges remain numerical stability and discretization accuracy, which can affect robustness if not carefully managed.

In summary, analytical methods are essential for their simplicity, efficiency, and role in structuring the research process. By providing rapid insights, they guide experimental setups and CFD modeling, ensuring high-fidelity resources are applied where most needed. While their reliance on simplifying assumptions limits accuracy in complex flows, their utility in design guidance, validation, and methodological integration remains significant.

2.2. Wind Tunnel Experimental Methods

Wind tunnel experiments are a standard approach for studying aerodynamic problems. They provide controlled and repeatable conditions, producing stable, high-fidelity data that capture real-world feedback. Typically, scaled models are equipped with sensors and visualization systems such as Particle Image Velocimetry (PIV), enabling researchers to observe flow motion, vortex formation, dynamic wakes, and unsteady responses that analytical solutions or CFD may not fully capture. While wind tunnels offer direct and accurate measurements, their use involves challenges such as scale effects, blockage constraints, and high costs.

He et al. reviewed state-of-the-art wind tunnel studies for wind turbines, emphasizing how setups ranging from subscale to near full-scale address different aerodynamic questions [7]. They highlight that experimental data are crucial for validating both analytical models and CFD simulations, especially under nonlinear or turbulent conditions where theory fails. The main strength of wind tunnel testing lies in its physical realism, although reproducing atmospheric turbulence and gusts within a confined tunnel remains difficult. Despite these challenges, wind tunnels provide critical baselines to assess the accuracy of computational predictions.

The UNAFLOW project, described by Madsen et al., illustrates these trade-offs in practice [8]. By subjecting floating wind turbine models to controlled surge motions across three operating conditions (Table 1), the team replicated dynamic inflow effects rarely captured in numerical or analytical studies. Using pressure sensors and flow visualization, they measured unsteady aerodynamic loads and wake interactions affecting turbine stability. However, Madsen et al. also note the difficulties of scaling model data to full-size turbines, as experimental fidelity is limited by dimensionless scaling laws. This example underscores why wind tunnel experiments are often combined with CFD to leverage their complementary strengths.

Table 1. Tested wind turbine operating conditions (V is average wind speed, RS is rotor speed, and β is blade pitch angle)

Condition	V (m/s)	RS (rpm)	TSR[-]	β
RATED 1	2.5	150	7.5	0
RATED 2	4	241	7.5	0
ABOVE	6	265	5.5	12.5

To address the inherent limitations of traditional wind tunnel testing, Chowdhury et al. propose integrating wind tunnel experiments with digital twin frameworks. While wind tunnel testing provides essential empirical data, it faces constraints such as limited scalability and difficulty in replicating real-world conditions accurately. By combining real-time experimental measurements with computational simulations, digital twins generate virtual models that enhance understanding and predictive accuracy across a wider range of conditions.

Chowdhury et al. validated RANS simulations by comparing them with wind tunnel measurements of turbulence kinetic energy k and dissipation rate λ behind a grid [9]. The hot-wire measurement setup for the wake of a regular grid (side view) is shown in Fig. 2. These experimental data serve as benchmark references for RANS validation, demonstrating close agreement between simulations and measurements.

By integrating experiments and simulations, the digital twin approach overcomes the scale and cost limitations of physical testing while reducing uncertainties in computational models. It combines the reliability of experimental data with the flexibility of simulations, enabling exploration of conditions beyond the practical reach of wind tunnels. This method provides a more robust and comprehensive understanding of aerodynamic behavior, improving prediction accuracy and the overall efficiency of the validation process.

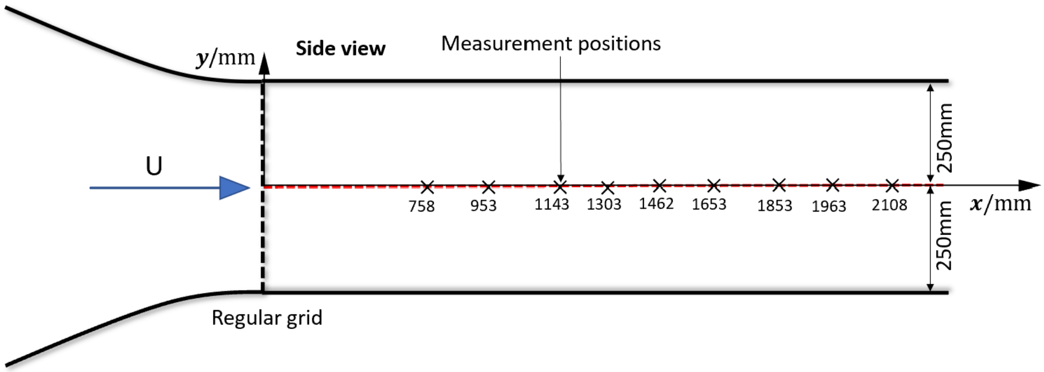

Figure 2. Schematic diagram of the experimental set-up for hot-wire measurements in the wake of a regular grid (side view)

Overall, wind tunnel experiments occupy a unique position: they remain indispensable for validating flow physics and generating empirical benchmarks, but they are most effective when combined with computational tools.

2.3. Computational Fluid Dynamics (CFD) Methods

Computational Fluid Dynamics (CFD) studies fluid mechanics through computational simulations. Its key advantage is the ability to calculate quantities such as pressure distributions, vortex structures, and turbulent wakes by solving the Navier–Stokes equations using models like RANS, LES, and DNS, each representing a trade-off between accuracy and computational cost.

Lee et al. reviewed modern CFD approaches, comparing RANS, LES, DNS, and hybrid models in terms of computational cost and accuracy [10]. Their study highlights the widespread use of RANS for steady-state engineering applications due to its low computational cost. LES and DNS, by contrast, provide detailed simulations of turbulence and vortical structures but require substantially more computational resources. They emphasize that selecting an appropriate model is critical, as it significantly affects prediction accuracy.

Kumar et al. note that CFD performs best when guided by analytical methods and validated against experimental data [4]. CFD enhances theoretical predictions by providing detailed parameters such as separation points, lift-to-drag ratios, and wake dynamics. The main risks of CFD arise from discrepancies with real-world physics, caused by turbulence modeling uncertainties, boundary conditions, or discretization schemes if not validated. Therefore, integrating analytical, experimental, and computational methods ensures more consistent and reliable results.

Zhang et al. reviewed CFD applications in engineering, particularly for assessing wind effects on tall buildings [11]. Their study demonstrates that CFD can evaluate wind loads, vortex-induced vibrations, and pedestrian-level wind comfort, offering an alternative to expensive experiments. However, CFD accuracy depends on assumptions such as turbulence closure models and numerical discretization. Fig. 3, showing a comparison between polyhedral and Hex-Tet meshes for a super-tall structure, illustrates the importance of empirical validation to ensure reliable CFD predictions.

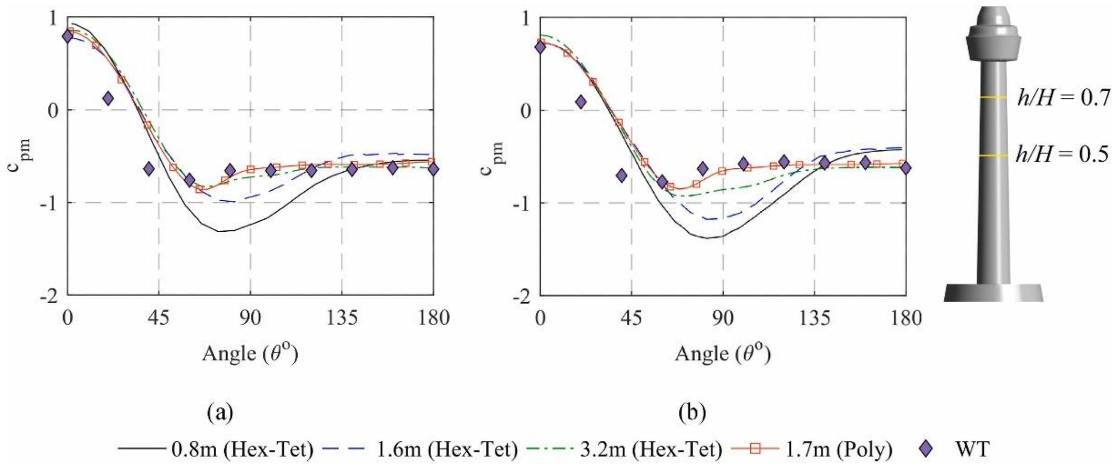

Figure 3. Comparison of Polyhedral mesh and Hex-Tet mesh of a super-tall structure

3. Summary

The combination of analytical methods, wind tunnel experiments, and CFD has driven the development of fluid mechanics. Analytical methods provide fast, low-cost predictions, though they are less accurate, particularly in turbulent or highly nonlinear flows. Wind tunnel experiments deliver high-fidelity data, capturing real-world feedback, making them the most precise method for studying flow behavior. However, their high cost and scale limitations restrict their applicability. CFD solves the Navier–Stokes equations numerically, offering flexible and wide-ranging applications, but it requires careful model selection and significant computational resources. Integrating these methods, for example, using digital twins combined with wind tunnel data, represents a promising direction for future research.

In conclusion, each method contributes uniquely to aerodynamic research. Analytical methods offer efficient, low-cost results for early-stage design. Wind tunnel experiments serve as the gold standard, providing data to validate analytical and CFD models. CFD enables simulations across diverse conditions and allows adaptation of models to specific scenarios. While each method has its advantages and limitations, an integrated approach maximizes performance and minimizes drawbacks. The incorporation of digital twins with physical testing, for instance, holds significant potential for optimizing aerodynamic designs, enhancing reliability, and reducing development time.

References

[1] Frolov V, Petrov A, Volkov Y. Data-driven modal decomposition methods for flow feature extraction: Application to unsteady flows over airfoils. Journal of Fluid Mechanics, 2023, 915: A10.

[2] Guo Z, Liu X, Wang H. Wind tunnel testing and PIV analysis of turbulent inflows and rotor aerodynamics for wind turbine optimization. Renewable Energy, 2022, 184: 211 – 222.

[3] Zhang Y, Li J, Xu Q. CFD simulations for wind-induced vibration analysis of tall buildings. Building and Environment, 2021, 193: 107634.

[4] Kumar JK, Prabhu KS, Srinivas G. A comprehensive review of aerodynamic performance evaluation for aircraft wings and engines: insights into experimental, numerical, and theoretical approaches. Aerospace Systems, 2025, 10 (1): 1 – 15.

[5] Wei C, Huang J, Song L. Study on a rapid aerodynamic optimization method of flying wing aircraft for conceptual design. International Journal of Aerospace Engineering, 2022, Article ID 5775355.

[6] Liu Y, Zhang Y, Wang Z. Review of vortex methods for rotor aerodynamics and wake dynamics. Advances in Aerodynamics, 2022, 4 (1): 20.

[7] He X, Li Y, Wang T. Wind tunnel tests for wind turbines: A state-of-the-art review. Renewable and Sustainable Energy Reviews, 2022, 159: 112 – 125.

[8] Madsen P, Jensen L, Sørensen H. UNAFLOW: a holistic wind tunnel experiment about the aerodynamic response of floating wind turbines under imposed surge motion. Wind Energy Science, 2021, 6: 1169 – 1184.

[9] Chowdhury A, Rahman M, Islam S. Developing a digital twin framework for wind tunnel testing: validation of turbulent inflow and airfoil load applications. Wind Energy Science, 2024, 9: 235 – 252.

[10] Ahmed S, Li J, Thompson R. State-of-the-art CFD simulation: a review of techniques, validation methods, and application scenarios. Journal of Recent Trends in Mechanics, 2024, 10 (3): 45 – 68.

[11] Zhang L, Wu H, Chen Y. A technical review of computational fluid dynamics (CFD) applications on wind design of tall buildings and structures: past, present and future. Journal of Building Engineering, 2023, 69: 104 – 121.