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Review of qualitative experimental methods for visualising airflow around aircraft mock-ups in wind tunnels

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Abstract. Around aerodynamic models in the subsonic tunnel, there are several qualitative experimental methods of visualising airflow that can provide valuable information about their aerodynamic behaviour. These methods allow researchers to visualise how air moves around the model and to observe complex phenomena such as flow separation. These qualitative experimental methods of visualising airflow provide a visual understanding of aerodynamic behaviour and allow researchers to identify and analyse complex phenomena that occur around aerodynamic models in the subsonic tunnel. By using these methods, valuable data is obtained that can be used to improve aerodynamic design and develop advanced technologies.
Keywords: *aerodynamic models, subsonic tunnel, qualitative experimental methods, advanced technologies, flow separation*

Introduction

Qualitative methods of visualizing airflow around aerodynamic models are of significant importance in the field of aerodynamics for several reasons:

- Understanding complex phenomena: Qualitative visualisation methods provide a direct and intuitive insight into airflow behaviour[1]. They allow us to identify complex phenomena such as flow separation, separation zone, vortices, and better understand them.
- Performance evaluation of aerodynamic models: Qualitative visualization helps to evaluate the performance of aerodynamic models in a more interactive way[2]. We can observe in real time how different model changes affect airflow and identify potential problem areas or improvements.
- Validate numerical simulations: Qualitative visualization is essential in validating the results obtained from numerical simulations[3]. Comparing experimental data with numerical results ensures the correctness of the model used in the simulations and increases confidence in the results obtained.
- Aerodynamic design optimisation: Qualitative visualisation methods facilitate aerodynamic design optimisation[4]. Visual observation of the model during testing provides valuable clues to identify areas of high aerodynamic drag and identify potential improvements.

- Development of advanced technologies: Qualitative visualisation provides a solid basis for the development of advanced aerodynamic technologies[5]. Understanding complex phenomena enables the identification of innovative and effective aerodynamic solutions.
- Education and communication: Qualitative visualisation methods are also used for educational purposes, helping students and young researchers to better understand the principles of aerodynamics and fluid behaviour.
- Applicability in industry: Qualitative visualisation methods are used in industry to assess the aerodynamic performance of vehicles, aircraft, structures and other objects, contributing to the development of more efficient and safer products[6].

In conclusion, qualitative methods for visualising airflow around aerodynamic models are essential to advance aerodynamics and develop innovative and efficient solutions in various industries[7]. These methods bring significant benefits in research, development and production, contributing to the advancement of science and technology.

Qualitative wire method applied to an aerodynamic model

Visualizing airflow around an aerodynamic model using the wire method is a classic experimental technique used in aerodynamics[8]. This method involves placing thin, fine wires near the aerodynamic model and observing how they move under the influence of airflow.

The experimental steps, Figure 1, carried out in this chapter to visualise the airflow pattern using the wire method can be seen in next figure.

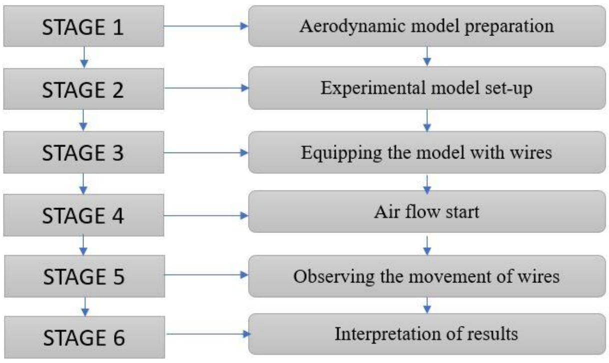

Figure 1. Experimental steps for the qualitative wire visualization method.

This wireframe method of visualization provides a visual and intuitive view of airflow and can help identify complex aerodynamic phenomena. The aerodynamic model tested in this research study was mounted on the three external balance supports, this was used to measure the loads transmitted from the model in the test section[9].

In this experimental study we performed visualizations using wires to get a qualitative picture of the overall air motion. The wires were placed on the two wings and the tail of the plane. The angle at which the airflow breaks up and the symmetry between the two wings was observed from this point of view. The placement of the wires on the model surface can be seen in Figure 2. The model thus prepared is installed in the experimental area of the wind tunnel, where by setting the current in motion, the wires will be placed along the local velocity direction at the model surface and can indicate the instability or detachment regimes.

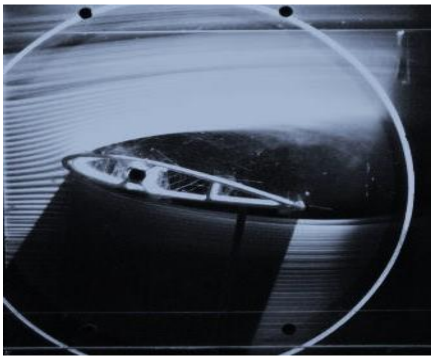

Figure 2. Aerodynamic model equipped with wires.

As long as the boundary layer on the pattern is laminar, the yarns in this layer remain quiet. From the transition point they begin to visibly vibrate, oscillating strongly in the turbulent boundary layer, and the break-ups along the wing span can thus be easily followed by observing the wires.

Qualitative method of PIV visualization applied to an aerodynamic model

The qualitative PIV (Particle Image Velocimetry) visualisation method is an advanced technique used to visualise and measure airflow around an aerodynamic model[10]. PIV is a non-intrusive and non-invasive method that uses small particles (such as smoke particles, aerosols or fluorescent particles) to track fluid motion and obtain detailed information about the velocity and direction fields of the airflow[11].

The PIV visualisation, Figure 3, process applied to an aerodynamic model involves the following steps:

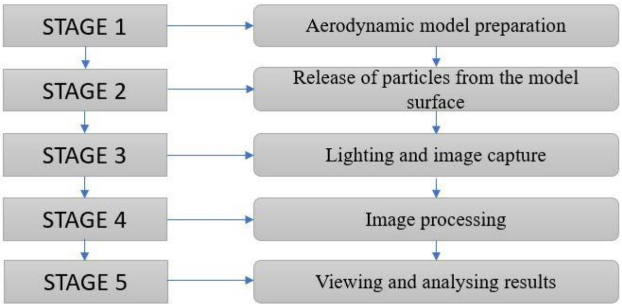

Figure 3. Experimental steps for the qualitative PIV visualisation method.

This is an optical measurement technique considered to be non-intrusive, which uses a laser plane as a light source to illuminate particles and allows the flow and turbulence field in the experimental chamber to be tracked and involves the intercorrelation of the recorded images.

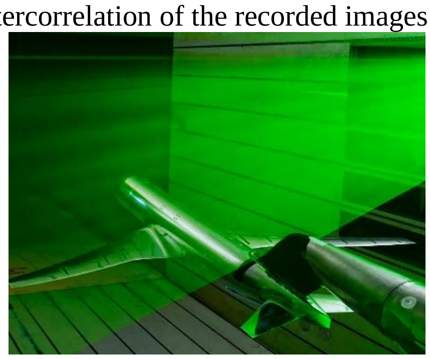

Figure 4. Results of experiments using the PIV system.

The air inside the wind tunnel is pre-filled with fine solid or liquid particles. The essential principle of this measurement method is the determination of local flow velocities from particle displacements[12].

This method also offers the possibility to have a feedback during the tests which allows the visualization of partial results leading to greater flexibility and adaptability according to the respective technical requirements[13].
The qualitative PIV visualisation method, Figure 4, offers significant advantages in the study of aerodynamics, as it allows detailed information on airflow to be obtained in real time and under unrestricted conditions. This facilitates the identification of complex phenomena such as flow separation and helps to optimise aerodynamic design to achieve desired performance[14]. In addition, the PIV method can also be used in the validation process of numerical simulation results, providing a direct comparison between experimental data and simulated results.

Qualitative visualization method of PSP visualization applied to an aerodynamic model
The Pressure-Sensitive Paint (PSP) qualitative visualisation method is an advanced technique used to visualise and measure the pressure distribution on the surface of an aerodynamic model during aerodynamic testing[15]. This method is non-intrusive and allows a complete map of the pressure distribution on the model surface to be obtained, providing valuable information on aerodynamic behaviour and drag.
The PSP visualisation, Figure 5, process applied to an aerodynamic model involves the following steps:

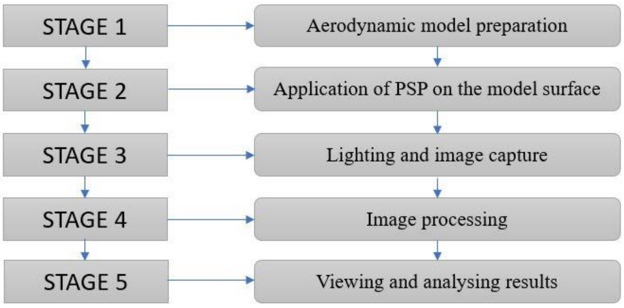

Figure 5. Experimental steps for the qualitative PSP visualisation method.

After preparation of the aerodynamic model a thin film of PSP was applied to the surface of the aerodynamic model. This film contains pressure-sensitive molecules, which change their fluorescent properties depending on the air pressure acting on them. The surface of the PSP-coated model is illuminated with an ultraviolet light source. Under the influence of UV light, the PSP film emits fluorescent light, and the intensity of this light is related to the air pressure at the pattern surface. Luminescence images are captured with a high sensitivity camera. The captured images are processed to obtain information about the pressure distribution on the model surface. By comparing the luminescence with a pre-calibration, accurate data can be obtained about the air pressure at different points on the model.

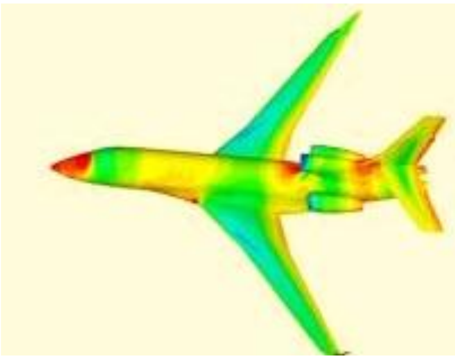

Figure 6. Results of experiments using the PSP system.

The PSP results, Figure 6, are visualised as a coloured map of the pressure distribution on the surface of the aerodynamic model. This visualisation allows a direct and detailed visual understanding of the air pressure behaviour around the model. The qualitative PSP visualisation method is valuable in the study of aerodynamics as it provides essential information about the pressure distribution on the model surface, allowing researchers to identify areas of high or low pressure and to assess aerodynamic behaviour under different conditions. This advanced technique is used in aerodynamic research, aerospace and vehicle development to optimise the design and performance of aerodynamic models.

Conclusion

Flow visualization techniques in subsonic wind tunnels serve the purpose of making the airflow patterns visible and aiding in the understanding of aerodynamic phenomena.

Table 1. Difference between flow visualization in subsonic wind tunnels

Aspect	Wire Visualization	PIV Visualization	PSP Visualization
Principle	Thin wires or threads	Particle tracers	Pressure-sensitive paint
Data type	Qualitative	Qualitative velocity fields	Quantitative pressure distribution
Data resolution	Low	High spatial and temporal resolution	High spatial resolution
Setup Complexity	Simple	Complex	Moderate complexity
Intrusiveness	High	Moderate	Low
Cost	Low	Moderate to high	Moderate to High
Application	Quick qualitative assesment	Detailed quantitative velocity fields analysis	Pressure distribution on the model`s surface

In summary, Table 1, wire visualization is a qualitative method suitable for initial observations, while PIV and PSP offer quantitative data on the velocity and pressure fields, respectively, providing more in-depth insights into aerodynamic behavior in subsonic wind tunnels.

Qualitative experimental methods for visualizing airflow around aircraft mock-ups in wind tunnels play a crucial role in aerodynamic research and development. These methods provide valuable insights into the complex aerodynamic interactions that occur during flight. In conclusion, several key points can be highlighted:

- Visualization Techniques: Qualitative methods, such as smoke flow visualization, tuft testing, and surface oil flow, allow researchers to observe and understand the patterns of airflow around aircraft models. These techniques offer a visual representation of the aerodynamic behavior, aiding in the identification of areas with high turbulence, separation, or other flow phenomena;
- Insight into Flow Characteristics: These methods provide researchers with a qualitative understanding of flow characteristics, including boundary layer behavior, vortex shedding, and flow separation. Such insights are crucial for optimizing the design of aircraft components to enhance performance, stability, and fuel efficiency;
- Model Validation: Visualizing airflow around aircraft mock-ups helps validate computational models and simulations. By comparing experimental results with theoretical predictions, researchers can improve the accuracy of numerical models, ensuring that simulations more closely align with real-world aerodynamic behavior;
- Design Optimization: The qualitative data obtained from wind tunnel experiments inform the design process. Engineers can identify and address aerodynamic issues early in the design phase, leading to more efficient and safer aircraft configurations;

- Understanding Aerodynamic Phenomena: Visualization methods contribute to a deeper understanding of aerodynamic phenomena, such as wingtip vortices, flow separation, and wake interactions. This understanding is essential for developing innovative solutions to improve aircraft performance and reduce drag;
- Educational Value: Qualitative experiments in wind tunnels offer educational benefits by providing students and researchers with tangible examples of aerodynamic principles. The hands-on experience of observing and analyzing airflow patterns enhances learning and fosters a practical understanding of aerodynamics;
- Challenges: Despite the advantages, qualitative experimental methods may have limitations, such as the inability to quantify certain parameters. Combining qualitative techniques with quantitative methods can address these challenges and provide a more comprehensive understanding of the aerodynamic environment.

In conclusion, qualitative experimental methods for visualizing airflow in wind tunnels are indispensable tools in aerospace research. They contribute significantly to the advancement of aerodynamics, aiding in aircraft design, performance optimization, and the development of more efficient and safer aviation technologies.

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