

ON THE GROUND AND IN FLIGHT: AERODYNAMIC AND AEROELASTIC TESTING SUPPORTING INNOVATION IN AERONAUTICS

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1. Introduction

The path that leads complex technological innovations from theoretical concept to practical application is paved by a series of rigorous testing activities. The steps made in this technology development process are commonly formalized by the “Technology Readiness Level” (TRL) scale [1], visualized in Figure 1. In the context of aeronautics research and development, testing activities can be generally categorized into ground testing and flight testing, where the latter naturally succeeds the former in terms of technology maturity. Ground testing encompasses a very wide range of activities in terms of maturity [2], including component testing, integration testing and sometimes full system testing (TRL 3-7). Flight tests typically focus on full system testing (TRL 7-9) [3], with the exception of sub-scale experimental and testbed-type aircraft (TRL 3-6). Both types of testing cover various technical disciplines such as propulsion, structures, aerodynamics, and avionics.

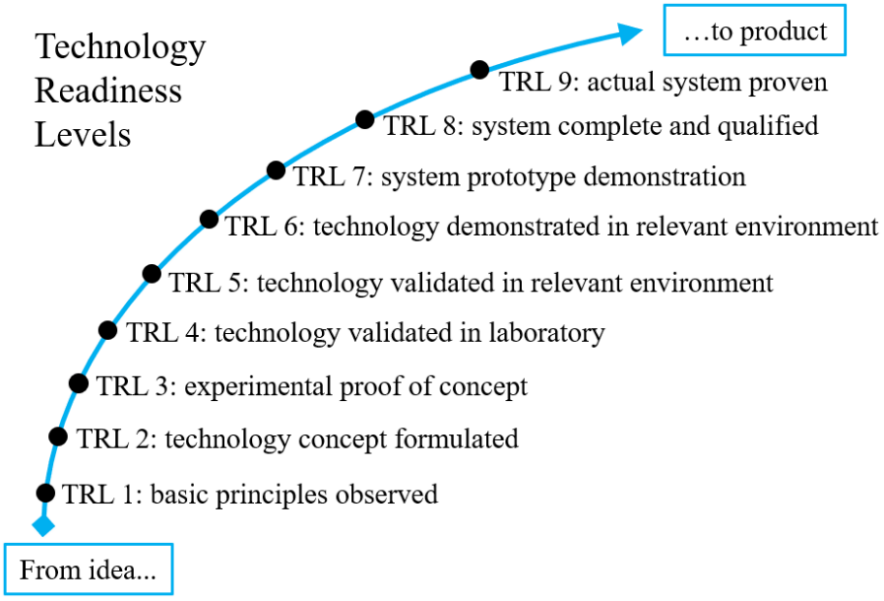


Figure 1 – Technology readiness levels (see [1]).

For aerodynamics and aeroelasticity, ground testing usually refers to wind tunnel testing, which is very widely used for both fundamental technology research and product development testing of novel and innovative designs. In contrast, flight testing, in the conventional sense of full-scale prototype flight tests, is typically used only for validation purposes in these disciplines. At the product development stage where such prototype flight tests can be conducted (TRL 7-9), it is indispensable that a deep understanding of the aerodynamic and aeroelastic behavior has already been obtained. New physical insights gained into these disciplines, such as the occurrence of premature boundary layer transition or unexpected flutter onset, are highly undesirable at this stage as they may require costly redesigns. It is therefore imperative to acquire the maximum amount of information possible

from ground testing to inform the prototype design. Research on advancing the test and measurement capabilities in the wind tunnel environment has been ongoing for many decades, and is continuously improving wind tunnel testing capabilities by providing more detailed insights into increasingly complex problems more efficiently (see, e.g. [4],[5],[6],[7],[8]).

A different approach to accelerate the development timelines in aeronautics that has gained traction in recent years is sub-scale experimental flight testing. By using downscaled aircraft models or flying testbed "donor" aircraft in flight tests, timelines and costs are drastically reduced compared to testing full-scale prototypes. This approach is particularly attractive for demonstrator-type testing (TRL 6), preceding prototype testing, where the goal is to "de-risk" novel aircraft technologies and designs, i.e. obtaining practical experience with all aspects of a novel aircraft technology. Such testing activities can, besides technological insights, also increase public acceptance and stakeholder engagement of novel technologies. Sub-scale flight testing is furthermore being used for fundamental research topics where the wind tunnel is inadequate (TRL 3-5), such as dynamic flight maneuver tests and control system response to atmospheric disturbances (see, e.g. [9],[10],[11],[12],[13],[14]).

A comprehensive review on sub-scale flight testing from 2022 [14] concluded that sub-scale flight testing is complementary to ground testing, due its dynamic testing capabilities in contrast to static wind tunnel tests, and the wind tunnel's superiority in terms of measurement accuracy. In my presentation, I will discuss how this statement is challenged by my recent research in two different streams of activity, as described in the following two sections. Firstly, my doctoral research at Delft University of Technology involved the development of advanced testing and measurement approaches for dynamic aeroelastic experiments in the wind tunnel. This activity is described in the next section, which is extracted from my dissertation summary [15]. Secondly, my recent work at the Royal Netherlands Aerospace Centre targets the development of advanced in-flight measurement technology for novel sub-scale flying testbed aircraft.

2. Experimental aeroelastic characterization based on integrated optical measurements

A novel measurement approach for dynamic aeroelastic wind tunnel testing was introduced. The key novelty of this approach is the integrated measurement of aerodynamic and structural quantities using an optical technique. The considered approach consists of combined measurements of flow tracer particles and structural markers using a Lagrangian particle tracking system. Based on these measurements, the quantities of interest for the characterization of a dynamic aeroelastic interaction, which are the three forces in Collar's triangle (aerodynamic, elastic, and inertial, as shown in Figure 2), are determined.

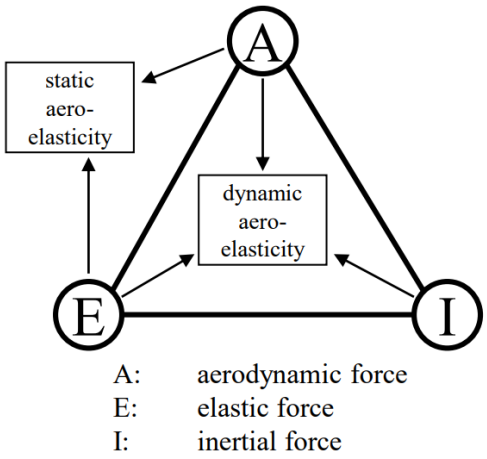


Figure 2 – Collar's triangle of forces.

Currently, measurements in aeroelastic wind tunnel tests are typically performed with individual sensors for each quantity of interest (pressure transducers, strain gauges, or accelerometers) that are installed inside the experimental model and/or with a force balance that measures the total loads acting on the model. The integrated optical measurement approach is an advancement over this

existing measurement technology because it provides field measurements of the aeroelastic structural response and the unsteady flow field around the experimental model, based on which the aerodynamic and structural load distributions can be determined, without requiring an instrumentation of the model with sensors. This measurement approach is therefore an effective way to produce experimental reference data to support the development process for innovations in aeronautics.

The development and application of the integrated optical measurement approach is discussed based on the measurements that were performed in three experimental campaigns in the wind tunnel. All three experiments are performed on a relatively large wind tunnel model scale, with dimensions on the order of 1m, which is a scale of high practical relevance for aeroelastic testing. The complexity of the three experiments, in terms of the aeroelastic phenomena that are observed, is increased incrementally, from a rigid-body motion, over a linear aeroelastic test case, to a nonlinear aeroelastic test case. Based on the observations and findings of the previous experiments, the data analysis methods for the subsequent experiments are selected and applied.

The first measurements with the integrated approach are performed on the rigid-body motion of a pitching wing with an actuated flap. Based on these measurements, two novel implementations of a non-intrusive aeroelastic loads determination method using flow field data are applied and assessed in a comparison with the data measured with installed pressure transducers, achieving good results. Furthermore, the structural motion of the wing is characterized based on the position measurements of structural markers on the wing surface in terms of the harmonically varying angle of attack and flap deflection. These results are validated against the input signal for the actuators that produce the structural motion, showing a very good agreement [16].

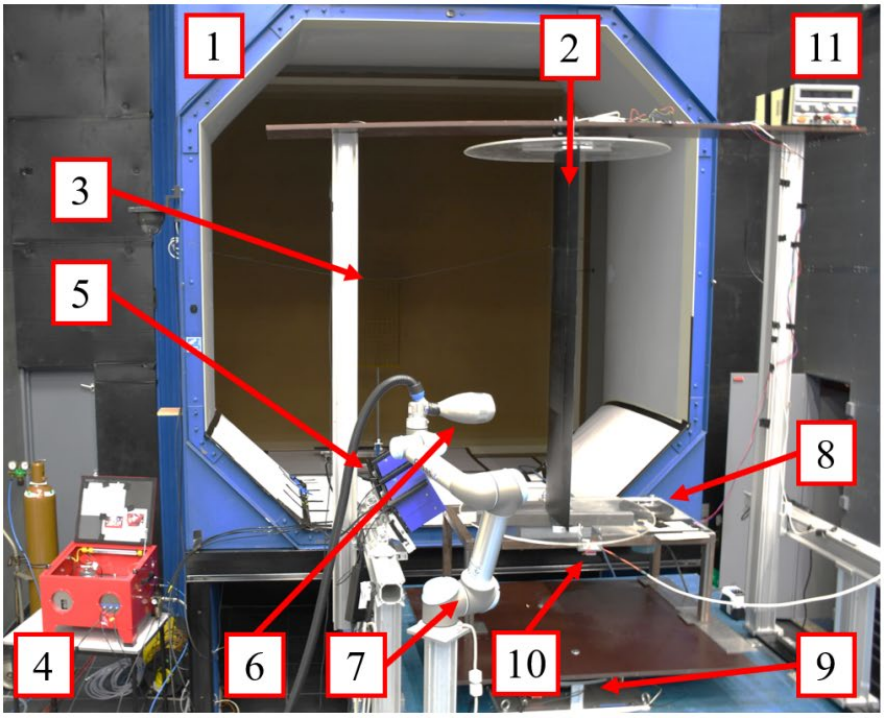


Figure 3 – Experimental setup of the first wind tunnel test

The second wind tunnel experiment is performed to provide a proof of concept of an aeroelastic characterization based on measurements with the integrated optical approach. For this experiment, measurements of one spanwise section of a flexible wing that is subjected to unsteady inflow conditions, which are produced by a gust generator, are conducted. The unsteady aerodynamic loads are determined based on the flow field measurements and the inertial and elastic loads are determined based on the structural deformation measurements using a simplified structural model of the wing. The experimental approach is validated by using these results to quantify the equilibrium of forces in Collar's triangle, thereby serving as a proof of concept for the aeroelastic characterization based on integrated optical measurements [17].

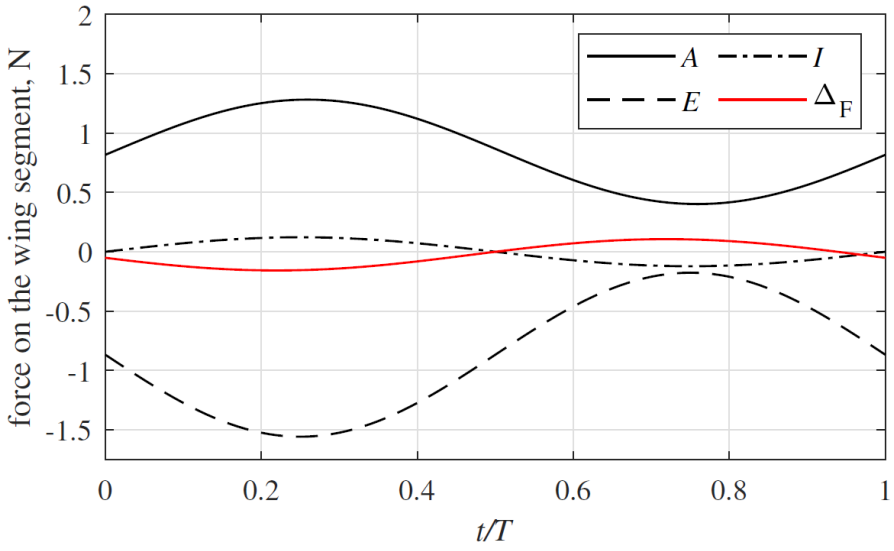


Figure 4 – Equilibrium of forces in Collar's triangle acting on a wing section, quantified by the measurement residual $\Delta_F = \boldsymbol{A} + \boldsymbol{E} + \boldsymbol{I}$ as measured with the integrated optical approach

The third experiment is performed using a highly flexible wing geometry that was studied as a benchmark case in the *Third Aeroelastic Prediction Workshop* [18]. The aeroelastic response of the highly flexible wing to steady and periodic gust inflow conditions is analyzed with the integrated measurement approach. Two different angles of attack and two different gust excitation frequencies are studied, producing linear and nonlinear aeroelastic effects. Advancing the work performed in the context of the proof of concept study, the aeroelastic loads along the entire span of the highly flexible wing are characterized. Furthermore, additional measurements of the structural and aerodynamic properties of the wing are conducted with a shape scan, a ground vibration test and infrared thermography measurements of the boundary layer on the suction side of the wing in the wind tunnel. The obtained results constitute a reference data set that is valuable for ongoing aeroelasticity research on improved nonlinear aeroelastic prediction methods [19].

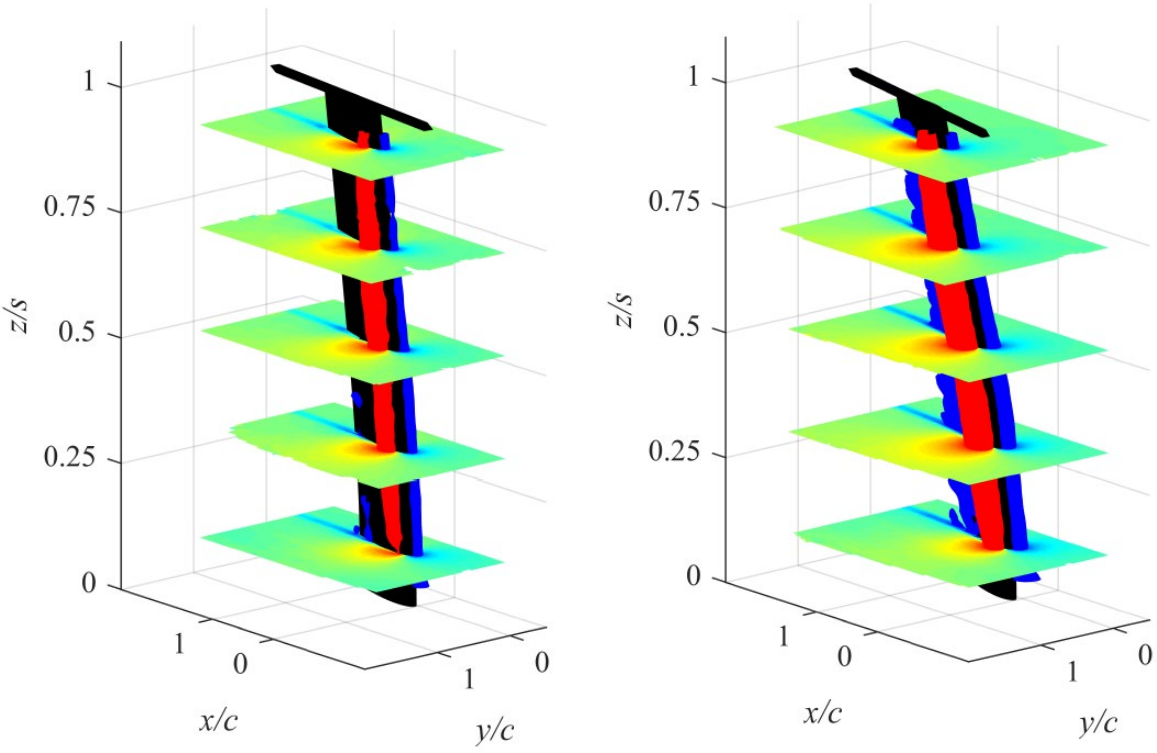


Figure 5 – Reconstructed Wing shape for two angles of attack, $\boldsymbol{\alpha} = \mathbf{5}°$ (left) and $\boldsymbol{\alpha} = \mathbf{10}°$ (right), with five slices of the streamwise velocity field and two isosurfaces of the streamwise velocity component

3. Advanced in-flight measurements for novel sub-scale experimental aircraft

The use of advanced measurement techniques, typically non-intrusive optical techniques that do not disturb the observed phenomenon, for applications in flight has been explored in the early 21st century, and it notably progressed through two large EU-funded international research projects: AIM (Advanced In-flight Measurement Techniques) and AIM^2 [21]. Among the techniques investigated in these projects are several techniques suitable for measuring aerodynamic or aeroelastic phenomena, such as image pattern correlation for structural deformation and displacement, particle image velocimetry, background oriented schlieren, infrared thermography and pressure sensitive paint [22]. All these techniques were originally developed for ground testing and adapted for in-flight application.

An interesting observation is that these developments were justified by an attempt to improve procedures during flight testing for aircraft certification (see [21]). It was discussed in the introduction that when flight tests for certification are performed (TRL 8-9), substantial theoretical knowledge and real-world test data about the designed product is already available. Arguably, this means that the application of advanced measurement technology lacks a significant part of its motivation, as a major benefit of these advanced technologies is to provide extensive field information without requiring complex sensor instrumentation. This leads to the conclusion that such techniques are naturally more useful for testing activities at lower technology maturity levels (TRL 3-5) than for certification testing.

Since the initial developments towards advanced in-flight measurements, low-TRL experimental flight testing with sub-scale models has gained significantly more traction. In the context of large EU-funded projects, the project EXAELIA [23] is the premier example of a new focus on this approach to testing. EXAELIA has the goal to accelerate the development of radically new, sustainable long-range aircraft and investigates the use of flying testbeds for de-risking their development by gaining in-flight experience with novel technologies early in the design phase [24]. Many of the largest design uncertainties studied in EXAELIA as key objectives for future flight tests are related to aerodynamics and aeroelasticity, for example the low-speed handling of blended wing body aircraft or the aeroelastic behavior of ultra-high aspect ratio wings.

In the context of EXAELIA, a new opportunity for advanced in-flight measurement techniques to gain significance thus presents itself in the form of their application to sub-scale experimental flight testing. The adaptation of the techniques to these tests comes with new challenges in measurement technology development, such as miniaturization of the technology for use onboard of sub-scale aircraft and remote controlled operation for the application on unmanned aerial vehicles. However, this new use case provides strong motivation to actively pursue these developments now, to have the measurement technology developed ready for the upcoming generation of experimental aircraft.

4. Conclusion and outlook

In the introduction, it was mentioned that the literature currently still considers ground testing and sub-scale flight testing as complimentary activities. It is the current understanding that both activities lead to higher technology maturity, and while ground testing offers superior measurement capabilities, sub-scale flight testing facilitates more complex dynamic tests. However, the two examples given in this presentation show that wind tunnel testing is currently developing capabilities for increasingly complex tests and advanced measurement technology is being developed for sub-scale flight tests, indicating that both testing approaches improve on their respective weaknesses. On one hand, this means that they challenge each other's territory, but on the other hand, it could also open the door to more interlinked test activities.

The costs and timelines associated with testing continue to make it an attractive option to investment in computational capabilities for aerodynamics and aeroelasticity, to reduce the amount of testing required. This process has been going on for decades and the increasing simulation capabilities challenge the traditional territory of wind tunnel tests more and more. In contrast, demonstrator-type flight testing with its importance for gaining public acceptance and stakeholder engagement experiences virtually no competition from even the most advanced computational simulation capabilities. For the future, it can thus be expected that the "right" path leading to this level of technology maturity continues to be disputed in the coming years, with interesting developments to be expected for aerodynamic and aeroelastic testing, both on the ground and in flight.

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