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On Subscale Flight Testing

Applications in Aircraft Conceptual Design

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To my parents

”

Aprender es el oficio más bonito del mundo.

Joan Roca, chef.

Abstract

Downscaled physical models, also referred to as subscale models, have played an essential role in the investigation of the complex physics of flight until the recent disruption of numerical simulation. Despite the fact that improvements in computational methods are slowly pushing experimental techniques towards a secondary role as verification or calibration tools, real-world testing of physical prototypes still provides an unmatched confidence. Physical models are very effective at revealing issues that are sometimes not correctly identified in the virtual domain, and hence can be a valuable complement to other design tools. But traditional wind-tunnel testing cannot always meet all of the requirements of modern aeronautical research and development. It is nowadays too expensive to use these scarce facilities to explore different design iterations during the initial stages of aircraft development, or to experiment with new and immature technologies.

Testing of free-flight subscale models, referred to as Subscale Flight Testing (SFT), could offer an affordable and low-risk alternative for complementing conventional techniques with both qualitative and quantitative information. The miniaturisation of mechatronic systems, the advances in rapid-prototyping techniques and power storage, as well as new manufacturing methods, currently enable the development of sophisticated test objects at scales that were impractical some decades ago. Moreover, the recent boom in the commercial drone industry has driven a quick development of specialised electronics and sensors, which offer nowadays surprising capabilities at competitive prices. These recent technological disruptions have significantly altered the cost-benefit function of SFT and it is necessary to re-evaluate its potential in the contemporary aircraft development context.

This thesis aims to increase the comprehension and knowledge of the SFT method in order to define a practical framework for its use in aircraft design; focusing on low-cost, short-time solutions that don't require more than a small organization and few resources. This objective is approached from a theoretical point of view by means of an analysis of the physical and practical limitations of the scaling laws; and from an empirical point of view by means of field experiments aimed at identifying practical needs for equipment, methods, and

tools. A low-cost data acquisition system is developed and tested; a novel method for semi-automated flight testing in small airspaces is proposed; a set of tools for analysis and visualisation of flight data is presented; and it is also demonstrated that it is possible to explore and demonstrate new technology using SFT with a very limited amount of economic and human resources. All these, together with a theoretical review and contextualisation, contribute to increasing the comprehension and knowledge of the SFT method in general, and its potential applications in aircraft conceptual design in particular.

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Linköping, August 2018

A handwritten signature in black ink, appearing to read 'Alejandro Sobron', with a stylized, flowing script.

Alejandro Sobron

Abbreviations

ADC	Analog-to-Digital Converter
AGL	Above Ground Level
ALAN	Aircraft Log Analysis
AOA	Angle-Of-Attack
AOS	Angle-Of-Sideslip
BFF	Body Freedom Flutter
BVLOS	Beyond Visual Line-Of-Sight
BWB	Blended-Wing-Body
CAD	Computer-Aided Design
CFD	Computational Fluid Dynamics
CG	Centre of Gravity
CONOPS	Concept Of Operations
COTS	Commercial Off-The-Shelf
EKF	Extended Kalman filter
EVLOS	Extended Visual Line-Of-Sight
FCS	Flight Control System
FLUMES	Division of Fluid and Mechatronic Systems
GFF	Generic Future Fighter
GNSS	Global Navigation Satellite Systems
HPA	Human-Powered Aircraft
I/O	Input/Output
IMU	Inertial Measurement Unit
LSA	Light-Sport Aircraft
MEMS	Micro-Electro-Mechanical System
NASA	National Aeronautics and Space Administration of the United States
PCB	Printed Circuit Board
PIC	Pilot In Command
R/C	Radio Control
RPA	Remotely Piloted Aircraft
RPAS	Remotely Piloted Aircraft System
SFT	Subscale Flight Testing

STOL	Short Take-Off and Landing
TOM	Take-Off Mass
TRL	Technology Readiness Level
UAS	Unmanned Aircraft System
UAV	Unmanned Aerial Vehicle
USA	United States of America
VLOS	Visual Line-Of-Sight
VTOL	Vertical Take-Off and Landing

Nomenclature

A	Area	$[\text{m}^2]$
a	Linear acceleration	$[\text{m s}^{-2}]$
α	Angle of attack	$[\text{° or rad}]$
α'	Generalised aircraft attitude relative to airstream	$[\text{° or rad}]$
AR	Aspect ratio	$[-]$
β	Angle of sideslip	$[\text{° or rad}]$
c	Speed of sound (in the pertinent fluid)	$[\text{m s}^{-1}]$
D	Drag force	$[\text{N}]$
δ	Control surface deflection angle	$[\text{° or rad}]$
E	Modulus of elasticity	$[\text{Pa}]$
e	Span efficiency factor	$[-]$
EI	Bending stiffness	$[\text{N m}^2]$
F	Force	$[\text{N}]$
Fr	Froude number	$[-]$
g	Acceleration due to gravity	$[\text{m s}^{-2}]$
GJ	Torsional stiffness	$[\text{N m}^2]$
I	Mass moment of inertia	$[\text{kg m}^2]$
L	Lift force	$[\text{N}]$
l	Characteristic linear dimension	$[\text{m}]$
m	Mass	$[\text{kg}]$
M	Mach number (context dependent)	$[-]$

M	Moment (context dependent)	[N m]
μ	Dynamic (absolute) viscosity	[Pa s]
ν	Kinematic viscosity	[m ² s ⁻¹]
Ω	Generalised angular rate	[rad s ⁻¹]
ω	Frequency of oscillation	[rad s ⁻¹]
$\dot{\Omega}$	Generalised angular acceleration	[rad s ⁻²]
$\bar{p}$	Static pressure	[Pa]
Re	Reynolds number	[-]
ρ	Mass density (of the pertinent fluid)	[kg m ⁻³]
σ	Surface tension per unit length	[N m ⁻¹]
t	Time	[s]
τ	Time constant or reduced-time factor	[-]
V	Linear velocity	[m s ⁻¹]
W	Weight force	[N]
∞	Indicates free-stream reference value	
fs	Indicates full-scale value	
m	Indicates model value	

Papers

This thesis is based on the publications listed below which, from now on, will be referred to by their Roman numerals. These publications are presented in chronological order, and besides some minor formatting changes, they are reproduced here as they were originally published.

The author was the presenter and main contributor in all these papers, although he received additional contributions and support from the co-writers. A short summary of each paper is presented in Chapter 9.

- [I] Alejandro Sobron, David Lundström, Ingo Staack, and Petter Krus. “Design and Testing of a Low-Cost Flight Control and Data Acquisition System for Unstable Subscale Aircraft”. In: *30th Congress of the International Council of the Aeronautical Sciences*. Daejeon, South Korea, 2016. ISBN: 9783932182853.
- [II] David Lundström, Alejandro Sobron, Petter Krus, Christopher Jouannet, and Roberto Gil Annes da Silva. “Subscale Flight Testing of a Generic Fighter Aircraft”. In: *30th Congress of the International Council of the Aeronautical Sciences*. Daejeon, South Korea, 2016. ISBN: 9783932182853.
- [III] Alejandro Sobron, David Lundström, Roger Larsson, Petter Krus, and Christopher Jouannet. “Methods for efficient flight testing and modelling of remotely piloted aircraft within visual line-of-sight”. In: *31st Congress of the International Council of the Aeronautical Sciences*. Belo Horizonte, Brazil, 2018.

Other publications

The following publications are not directly included in this thesis, although they constitute an important part of the background.

- [V] Alejandro Sobron. “Design and Testing of a Flight Control System for Unstable Subscale Aircraft”. Master’s thesis. Linköping University, 2015.
- [VI] Christopher Jouannet, David Lundström, Petter Krus, Alejandro Sobron, Roberto Gil Annes da Silva, Fernando Catalano, and Paulo Greco. “Aerodynamic databased of a subscale demonstrator”. In: *35th AIAA Applied Aerodynamics Conference*. Denver, CO, USA: AIAA, 2017. ISBN: 9781624105012.
- [VII] Alejandro Sobron, David Lundström, Petter Krus, Christopher Jouannet, and Luiz C. S. Góes. “Flight test design for remotely-piloted aircraft in confined airspace”. In: *6th CEAS Air and Space Conference, Aerospace Europe*. Bucharest, Romania, 2017, pp. 260–269.
- [VIII] Diego de Matos Monteiro, Leonardo Murilo Nepomuceno, Roberto Gil Annes da Silva, Marcos da Silva e Souza, Flávio José Silvestre, Petter Krus, and Alejandro Sobron. “Subscale Flight Test Model Development and Testing as a Tool for Unconventional Aircraft Design”. In: *6th CEAS Air and Space Conference, Aerospace Europe*. Bucharest, Romania, 2017, p. 495.

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1

Introduction

Experimental techniques have traditionally been the backbone of aeronautical technology since its birth. Aircraft are complex machines that make use of also complex natural phenomena which, in some cases, were anticipated and exploited much before they were completely understood. Some problems, such as the inherent nonlinearity of the Navier-Stokes equations that govern fluid dynamics, remain still unresolved and its study requires a combination of experiments and numerical approximations.

Downscaled physical models, here referred to as *subscale* models, have played an essential role in the practical investigations that tried to understand the complex physics of flight. Aviation pioneers, such as the Wright brothers, already performed systematic tests with subscale models during the early days of aircraft design [1]. Later on, placing captive subscale models inside wind tunnels became the major source of information for technological aerodynamics and aeronautical applications; a methodology that remained unchallenged until the recent disruption of numerical simulation [2].

Despite the fact that improvements in computational capability and numerical simulation are slowly pushing experimental techniques towards a secondary role as verification or calibration tools, real-world testing of physical objects still provides an unmatched confidence and, occasionally, may also reveal issues that were not correctly identified in the *virtual domain*. In the words of Kress: “[Physical models] may even spade up potential problems you wish you had never seen!” [3]. In some cases, testing physical prototypes might not only be a cost-effective complement to other design tools, but also might expedite the development process [4].

Traditional wind-tunnel testing cannot always meet all of the requirements of modern aeronautical research and development. Wind tunnel facilities are nowadays scarce, costly to operate, and their testing rigs often have limited degrees of freedom. It is too expensive to use these facilities to explore different design iterations during the initial stages of aircraft development, or to experiment with new technologies at low Technology Readiness Levels (TRLs). In

some cases, testing of free-flight subscale models, referred to as Subscale Flight Testing (SFT), could offer an affordable alternative. On one hand, being free from the inherent physical limitations of a wind-tunnel rig facilitates the study of flight dynamics. On the other hand, data acquisition becomes more difficult and the inability of modifying the atmospheric conditions as desired does introduce important limitations associated with the relative scale of the test article.

In aviation, “small” and “light” are often synonyms of “economical” and “low-risk”. The miniaturisation of mechatronic systems, the advances in rapid-prototyping techniques and power storage, as well as new manufacturing methods, currently enable the development of sophisticated models at scales that were impractical some decades ago. Moreover, the recent boom in the commercial drone industry has driven a quick development of specialised electronics and sensors which offer nowadays surprising capabilities at competitive prices. There is hence a renovated opportunity to use Subscale Flight Testing (SFT) as a cost-effective development tool that could complement conventional techniques with both qualitative and quantitative information. This thesis tries to define a practical framework for the use of SFT focusing on low-cost, short-time solutions that could be suitable for small organizations with limited resources.

1.1 Background

The National Aeronautics and Space Administration of the United States (NASA) has historically been one of the most renowned actors in this field. Chambers [5] presents an extensive historical review of NASA’s research activities involving subscale models from the 1940s to 2008. Free-flying models, both remotely controlled and uncontrolled, have been used in low-speed tests considered of high risk, such as studying the dynamics of high Angle-Of-Attack (AOA), stall, departure, post-stall, and spin regimes. These studies typically comprised four different techniques: (1) small free-spinning models inside vertical wind tunnels, (2) free-flight inside large low-speed wind tunnels, (3) unpowered models dropped from manned aircraft, and (4) remotely-piloted models with their own propulsion system.

The use of small, unpowered and uncontrolled subscale models without instrumentation inside vertical wind tunnels became a common technique for researching developed spin already in the 1930s. Figure 1.1 shows a typical spin test, and a detailed description can be found in [6]. Although requiring very specialised facilities, this relatively simple technique has remained in use until modern times as seen in programmes such as the *X-31* [7], *F-18* [8], and *F-22* [5].

Free-flight testing models inside a wind tunnel usually requires a test section of considerable dimensions, such as the large open section of the *Full-Scale Tunnel* of NASA’s Langley Research Center [9]. According to Chambers, free-flight tests in this facility were common and they provided aerodynamic data

Figure 1.1 A subscale model of the Northrop XB-35 during a free-spinning test inside a vertical wind tunnel in NASA Langley Research Center in 1943. Courtesy of NASA (L-34796).

and predictions of high-AOA behaviour of every high-performance military aircraft developed in the United States of America (USA) during the 1970s and 1980s [9]. Figure 1.2 shows the preparation of two typical dynamically scaled models used in early free-flight tests. Besides military programmes, free-flight tests inside wind tunnels were also used to investigate wake encounters [10] and new civil concepts such as the Blended-Wing-Body (BWB) *X-48B*, which with a 3.8-meter wingspan became not only the largest but also the last free-flight model tested in the Langley Full-Scale Tunnel before its closure[9].

In order to increase the freedom for manoeuvring outside the limitations of a wind tunnel and the size of the subscale models, unpowered models dropped from manned aircraft have also been used in several military and research programmes. Some examples where the post-stall dynamics have been studied using these subscale *drop models* are the *X-31* [11, 7]; the *F-4*, *F-14*, *F-15*, *B-1* [5]; and the *F/A-18E/F* [12]. This technique has also been used for the study of space vehicles such as the NASA-Ames *M2-F1* vehicle [5], the Lockheed Martin *X-38* and the Japanese *HOPE-X* [13].

More advanced platforms emerged as progress was made in the fields of materials, electronics, computer science, power storage and communications. Modern subscale aircraft are often powered by their own internal propulsion systems and operate as conventional Remotely Piloted Aircraft System (RPAS). Two early examples of using this kind of vehicles for research and technology demonstration are the Rockwell *HiMAT* [14], and the multiple Radio Control (R/C) models of conceptual V/STOL aircraft tested by Grumman [3]. More recent technology demonstration projects include the NASA/McDonnell Douglas *X-36* [15], the NASA/Boeing *X-48B/C* BWB [16], and the BAE Systems research

Figure 1.2 A technician prepares dynamically scaled, free-flight models of the Bell X-1E and the Vought XF-8U Crusader for wind tunnel testing at NASA Langley Research Center in 1957. Courtesy of NASA (LRC-1957-B701_P-00660).

programme *FLAVIIR*, in which the subscale model *Eclipse* [17] was built and evaluated before proceeding to the development of the final demonstrator *Demon* [18]. A common factor in all these cases is that the configurations and the flight control solutions proposed are highly unconventional, and hence there is an aim to demonstrate their feasibility and acquire more data without the high cost and risk associated to a manned, full-scale vehicle.

Besides military and industrial developments, there are also other contemporary projects that use SFT as an airborne test facility for civil research purposes. A notable example is the NASA *AirSTAR* research programme [19] in which dynamically scaled models are used to explore an extended flight envelope and novel control laws for civil transport aircraft. The NASA *FASER* project uses instead low-cost models for research and demonstration of advanced dynamic modeling and control design concepts [20]. Another example of a pure research project with partners from both university and industry is the NACRE *Innovative Evaluation Platform* (IEP), in which a modular, dynamically-scaled aircraft is built to study environmental and safety issues [21, 22].

Various academic and research projects involving SFT have also been carried out recently by different universities, frequently under much lower budgets than those of the programmes mentioned before. The platforms used in these projects are in most cases derived from hobbyist R/C equipment and the models are usually not accurately scaled. Some examples of different implementations can be found in references [23, 24, 25, 26, 27, 28, 29].

1.1.1 Subscale Flight Testing in Sweden

In Sweden, the first notable examples of the utilisation of subscale models can be found during the development of the Saab 35 *Draken*. Its double delta wing with very small aspect ratio was certainly a radical design when it was first proposed in 1949. In order to reduce the uncertainties and the scepticism around this configuration, practical experiments were initially conducted with paper models, which were followed by numerous powered line-control models built to various scales and in various configurations. Dorr et al. [30] describe these experiments in detail: the line-control models, weighing about 6 kg and powered by pulsejet engines, were flown in a 19-meter-radius circular trajectory during approximately two minutes. The flight tests were filmed from the pilot's position and the information obtained was mostly a qualitative assessment of the low-speed behaviour and controllability with different tail configurations and Centre of Gravity (CG) locations. Figure 1.3 shows a picture of one of these models, in this case with a distinct nose intake design. According to Dorr et al., these experiments provided a significant insight into the double delta's flight characteristics and they also verified the conclusions reached by the engineering team, proving that such a design was feasible.

Figure 1.3 One of the line-control subscale models used during the initial development of the Saab 35 *Draken*, ca. 1949. Courtesy of Saab.

Another subscale test-bed was built directly after: the Saab 210 *Lilldraken* (little *Draken*) was a manned aircraft of approximately half the size of the final *Draken* and it was powered by a small turbojet engine. Developed solely as an experimental platform and first flown in 1952, the *Lilldraken* performed more than 1000 tests during the test programme and it played an important role in the evolution of the final design [30].

Furthermore, a subscale drop model was used for spin testing during the Saab 37 *Viggen* test programme in the 1960s according to Henriksson [31]. Later on, subscale platforms were used as technology demonstrators during the Saab *SHARC* and *FILUR* projects during the 2000s [32, 33].

1.1.2 Previous Research at Linköping University

At Linköping University, building and testing subscale demonstrators has traditionally been a distinctive part of the aeronautical education offered by the Division of Fluid and Mechatronic Systems (FLUMES). According to Jouannet et al., this activity provides aeronautical students with a fundamental holistic view of the entire design cycle of an aircraft and with a valuable experience of practical, applied work [34]. Numerous demonstrators have been designed and built during the last two decades, although most of these remained unpublished as local academic projects. Two exceptions are the demonstration of an *ECO-Sport* aircraft design [35], and the dynamically scaled demonstrator of a light business jet named *RAVEN*, a project which is described by Jouannet and Lundström in references [36, 37]. This demonstrator was equipped with an in-house data acquisition system and it was tested on the top of a moving car using a specially designed rig with three degrees of freedom, as shown in Figure 1.4. Indications of a possible stability problem prevented further flight testing.

Figure 1.4 *RAVEN*, the subscale demonstrator of a light business jet described in [37], mounted on a custom-made rig for car-top testing in 2008. Courtesy of David Lundström, Linköping University.

Amadori et al. manufactured and flight-tested a series of automatically designed micro-air-vehicles between 2008 and 2010 [38], a project that included the noteworthy achievement of carrying out the first documented flight test of

an entirely 3D-printed aircraft. A short summary of the SFT research activities at Linköping University around the year 2010 is given by Staack et al. in [39]. The research platforms available at that time already included a 13%-scale, Commercial Off-The-Shelf (COTS) model of a Dassault *Rafale* fighter aircraft, used mainly as a test-bed for systems and procedures. This model is shown in Figure 1.5. Lundström has been, in general, one of the main contributors to research on SFT and rapid prototyping at Linköping University during the recent years. His participation in these and other projects up to 2012 is summarised in [40].

Figure 1.5 Jet-powered, commercial model of a Dassault *Rafale* fighter at a 13%-scale, often used at Linköping University as a test-bed for systems and procedures.

Special mention has to be made of the Generic Future Fighter (GFF) project started in 2006 as a research collaboration between Saab Aeronautics, the Swedish Defence Research Agency (FOI), Volvo Aero, Linköping University and the Royal Institute of Technology (KTH). This project involved the conceptual design of a hypothetical next-generation fighter aircraft with stealth, super-cruise, and long range capabilities. The production of a 14%-scale remotely piloted demonstrator was awarded to Linköping University. The development of this jet-powered model, shown in Figure 1.6, is described in detail in references [41, 42].

The GFF subscale demonstrator was flown a few times between 2009 and 2010, but no formal flight testing campaign was conducted at that time and the integration of a data acquisition system fell outside the scope of the initial project. Being still today one of the most advanced research platforms at Linköping University, this aircraft has become a perfect test-bed for an important part of the work presented in this thesis: first, it represents a contemporary

Figure 1.6 *Demonstrator of the GFF, surrounded by most of its developers, soon after its completion in 2009. Courtesy of FLUMES, Linköping University.*

and relevant problem for the industry in which an unconventional configuration needs to be explored during the conceptual design phase. Second, the small size and relatively low cost of this platform fits well in the range of complexity in which this investigation wanted to focus on, i.e. considering the use of SFT in small companies or organizations with limited resources. Last, this platform is capable enough to integrate different types of equipment and therefore well-suited to demonstrate new technologies and methods.

1.2 Aim and Research Questions

Numerous examples of a successful application of SFT in aircraft research and development have been mentioned. Consequently, this research builds on from the hypothesis that SFT can be used during the aircraft conceptual design phase to obtain information, and reduce uncertainty and risk. However, the ratio between cost and benefit is a crucial factor for its application in industry. Recent disruptive innovations in the fields of electronics, computer science, manufacturing, power storage, and communications have significantly altered the cost and capabilities of small, flying vehicles such as subscale models. Therefore, a re-evaluation of SFT and its role in aircraft development is necessary.

The main aim of this research is to increase the comprehension and knowledge of the SFT method in order to evaluate the potential of a low-cost approach and its added value in the context of contemporary aircraft design.

More specifically, this thesis tries to answer three research questions that are formulated as it follows:

- RQ1:** Considering the physical and practical limitations of SFT, could this method still be useful to (economically) solve relevant problems in contemporary aircraft research and development?
- RQ2:** To what extent is it possible to use low-cost components and tools to gather and process (useful) data?
- RQ3:** What kind of flight testing methods and infrastructure would an organization need to safely perform SFT at a minimum cost?

1.3 Delimitations

The following delimitations should be taken into account:

- This thesis focuses on the implementation of SFT in contexts where both human and economic resources are limited. There is therefore a strong focus on low-cost solutions and short-time implementations.
- Where possible, the use of COTS components has been favoured for similar reasons.
- The experiments carried out here are aimed at verifying feasibility and functionality, not at producing high-fidelity data. In fact, this is not needed in many cases since the design is not frozen at early stages. In addition, validating or benchmarking the obtained aircraft characteristics might not be possible if no full-scale aircraft or experimental data are available.

- The empirical case study presented here is limited to a very reduced number of platforms.
- The flight testing methods proposed here are in part a consequence of the local regulations for civil air operations at the time that this work took place. Different conditions may apply at a different time or in other areas of the world.
- This thesis concerns mainly aspects such as platform development, flight testing, and data acquisition. No detailed discussions on algorithms for system identification or parameter estimation are intended.

1.4 Contribution

This thesis should be seen as an effort of integration rather than a particular high-end development. It has involved work in disciplines as diverse as electronics, computer programming, signal processing, experimental techniques, flight dynamics, flight testing and simulation.

The main objective has been approached from a theoretical point of view by means of an analysis of the physical and practical limitations of the scaling laws; and from an empirical point of view by means of field experiments aimed at identifying relevant issues regarding specific equipment, methods, and tools.

The main contributions are, in the opinion of this author, of technological nature: a low-cost data acquisition system is developed and tested; a novel method for semi-automated flight testing in small airspaces is proposed; a set of tools for analysis and visualisation of flight data is written; and it is also demonstrated that it is possible to research and demonstrate new technology using SFT with a very limited amount of economic and human resources. All these, together with a theoretical review and contextualisation, contribute to increasing the comprehension and knowledge of the SFT method in general, and its potential applications in aircraft conceptual design in particular.

1.5 Methodology

The presented research is, to a large extent, based on hypothetico-deductive principles [43] as illustrated in Figure 1.7. In addition, the process of evaluation or falsification has been largely empirical.

Figure 1.7 An empirical, hypothetico-deductive cycle.

The methodology used to conduct this work can be described in terms of three main domains:

- *Theory*, involving the established theories, rules, laws, and the predictions that can be drawn by observing reality.
- *Technology*, involving the methods, procedures, tools, and devices needed to make an activity possible.
- *Experiment and simulation*, involving the evaluation of such technology and proposed theories as well as exploring new phenomena.

Starting from an initial idea or hypothesis, the knowledge-forming process can be described as an iterative cycle of synthesis, adaptation, and analysis performed across these three domains at various hierarchical levels, similarly to the iterative process described by Brandt et al. [44] and also Hochwallner [45]. Figure 1.8 tries to illustrate this cycle as a spiral that leads to a final solution.

The *theory* domain is approached by means of a review of the published information on this field in addition to the analysis of the physical laws that govern the similarity principles. This analysis could be easily generalised over a wide range of scenarios and applications but, unfortunately, this is not the case for the technological and experimental domains.

The approach to *technology* and *experiment and simulation* is, in this case, largely empirical. Therefore, there is no possibility to cover a sufficiently wide range of cases, scenarios, and applications. These two aspects are approached with a case study, selected to be a representative example of the scenarios of

Figure 1.8 Design spiral conceived as an iterative cycle of synthesis, adaptation, and analysis. Adapted from [44].

interest: relatively small, low-cost SFT projects carried out by small organizations in a short time. The published paper appended to this thesis deal mainly with these two aspects.

Figure 1.9 illustrates this methodology and relates the different domains with the parts of this thesis.

Figure 1.9 Outline of the methodology used in this thesis: knowledge is increased following an iterative process of synthesis, adaptation, and analysis across the three domains at various hierarchical levels.

2

Opportunities in Aircraft Conceptual Design

Modern aircraft are tremendously complex products. Their development process involves high risks and it presents some special characteristics. This chapter offers a brief overview of the initial phases of such a process in order to provide a context for further discussion, and focusing on identifying the challenges and opportunities for Subscale Flight Testing (SFT).

2.1 Characteristics of the Aircraft Development Process

From a general product development perspective and according to the definitions given by Ulrich et al. [4], aircraft could be categorised as both high-risk products and complex systems: The high-risk of failure originates from the technical and market uncertainties as well as the high non-recurring costs. As a system, its extreme complexity is usually managed by decomposition into several subsystems and components that are often designed and developed in parallel.

For the success of such a development process it is therefore critical to identify the risks and track the propagation of uncertainty from the earliest time possible. In fact, early testing and validation are often conducted already at subsystem level without waiting for the final integration in order to reduce the degree of uncertainty. However, very little information is usually available during the earliest design phases.

As a consequence of the high complexity of the product, the uncertainty of the performance-estimation methods, and the usually sequential decision-making strategy, the aircraft design process typically suffers from a paradoxical disparity between the knowledge available and the design freedom along with committed cost [46, 47]; as illustrated in Figure 2.1. Unfortunately, important decisions affecting the total life-cycle cost of the aircraft are often taken under high degrees of uncertainty during the early design stages.

Figure 2.1 *Traditional design paradox in the aircraft development process, based on [46] and [47].*

These factors contribute to making aeronautics a relatively conservative industry in which empirical experience gathered from previous programmes plays a central role in any new project. However, empirical experience is often configuration-specific and hence it does not contribute to reduce the risk of radical or non-evolutionary designs [2]. It may be therefore deduced that one of the principal keys to innovation in aircraft development resides in the capability of estimating reliably and competitively the performance of the final product based on a limited set of information, especially during the early design phases.

2.2 The Aircraft Conceptual Design Phase

As a consequence of the factors described above, there is a strong interest in researching cost-effective methods that could be able to reliably estimate vehicle characteristics and, in general, to increase the available knowledge during the early phases of aircraft design.

There are several different interpretations of what can be considered as a typical aircraft development programme in the specialised literature, although most of them agree in dividing the aircraft design process in three general phases: conceptual, preliminary, and detail design [44, 46, 48, 49]. These three phases typically comprise all design activities from the initial project planning to the production ramp-up.

Figure 2.2 An interpretation of the initial design stages during a typical aircraft development process. The shadowed areas indicate where and how SFT could be an added value.

Assuming an aircraft development process whose initial structure looks as it is shown in Figure 2.2, this thesis sees potential benefits from the application of SFT during the first of these phases: the aircraft conceptual design. The functions covered in this phase do not consist only of design tasks but also of research, marketing, and management aspects. Among others, tasks typically included here are: identifying market opportunities, assessing new technologies, synthesising needs and forecasts into industrial strategies, investigating feasibility of product concepts, assessing production feasibility, and estimating life-cycle costs. This thesis believes that SFT can nowadays become a low-cost method that may assist the tasks of assessing and demonstrating new technologies, and also investigating feasibility and characteristics of proposed concepts.

Particularly in aircraft development, one of the main design tasks addressed in the conceptual phase is to find the most suitable configuration for a given set of requirements [50]. This is a highly multidisciplinary effort, although structure, aerodynamics, and stability & control are topics that traditionally play a central role. Within this task, SFT could be a competitive tool for the analysis of the last two: aerodynamics and stability & control.

Despite of externally resembling the full-scale product, subscale models used in SFT are not intended to fulfil the same prototyping functions as full-scale test aircraft. The latter are tremendously expensive, carefully planned prototypes not appropriate for design iterations, and their use is generally confined to the last stages of development when a large-scale, comprehensive verification of the product performance is required. According to the classification proposed by Ulrich et al. [4], the models used in SFT can be described as very focused physical prototypes, at a similar level of those used in wind-tunnel testing. Figure 2.3 illustrates these characteristics.

Figure 2.3 Characteristics of SFT models and technology demonstrators according to the prototype classification proposed by Ulrich et al. [4].

The reader should note that, unless specifically stated, the meaning of the term *model* is context dependant. Throughout this thesis, the term *model* is however used in most cases to designate a physical representation of a true object, generally of a different size but interconnected by some type of similarity.

According to Staack [50], the aircraft conceptual design phase is characterised for being:

- “**efficient**”, in terms of time, economic, and human resources;
- “**flexible**”, in terms of quick adaptability;
- “**transparent**”, in terms of favouring the comprehensibility and general understanding of the design problem;
- and “**multi-modal**”, in terms of enabling and making use of both manual and automated design modes.

These characteristics also indicate the different features that would be required from the tools and methods used during this design phase. In those terms, modern SFT could potentially offer:

- **Efficiency:** on the one hand, low cost thanks to the tremendous improvement in the price-performance ratio of miniaturised electronics. On the other, quick development times thanks to rapid prototyping methods. This method can be carried out by a reduced team and, additionally, it is suitable for outsourcing.
- **Flexibility:** the low cost and short time required for design-build-test iterations make this method relatively flexible in comparison to other traditional experimental techniques such as wind-tunnel testing.
- **Transparency:** physical prototypes, such as subscale models, are specially valuable for learning design features and communicating knowledge as well as being useful to detect unanticipated phenomena [4].
- **Compatibility with automation:** while this method may generally require manual and focused sub-design tasks to perform complete iterations, some parts of the process can be effectively automated and can be suited for optimisation. For instance, reference [38] is a good example of an agile framework for flight testing of automatically designed and 3D-printed micro air vehicles.

2.3 The Cost-Benefit Principle

Considering that numerous examples of a successful application of SFT in aircraft research & development have been already given in Section 1.1, the reader might question the need for further research. However, recent disruptive innovations motivate a re-evaluation of SFT and its potential applications: the progress made in the fields of electronics, computer science, manufacturing, power storage, and communications during the last two decades have totally altered the ratio between cost and benefit for the development of small, flying vehicles such as subscale models.

The cost reduction of capable microprocessors and solid-state sensors in addition to the increased availability of *open-source* software have been especially disruptive in many markets, such as mobile telephony and other consumer electronics. These enabling technologies are also partially responsible for the explosion of the consumer Unmanned Aerial Vehicle (UAV) market, the so-called *drone revolution* [51]. Figure 2.4, elaborated from data and predictions from different sources, illustrates some of these trends.

Figure 2.4 Cost trend of various electronic components and sales volume of related products during the last decade. *Data of Micro-Electro-Mechanical System (MEMS) components provided by [52]. **Data of smartphone sales provided originally by Gartner and retrieved from [53]. ***Data of drone sales provided by [54].

As in many other processes, the principle of *cost-benefit* also prevails in aircraft conceptual design. The main objective is here to maximise the information obtainable with a very limited amount of money, time, and human resources. Within these limits, any tool or method that provides more value than what it consumes would be desired. Moreover, according to Barlow, much design work is considered already successful if improvements are achieved, regardless of whether the methods used provide absolute accuracy in predicting all performance quantities of interest [55].

In this context, inexpensive models of very low complexity could still provide valuable information with respect to the invested resources. For physical aircraft prototypes in particular, as illustrated in Figure 2.5, the cost often escalates significantly with complexity and hence exhaustive prototypes are only valuable if real-world performance validation can be obtained. While with a limited impact in high-end systems, the improvement of the enabling technologies discussed before contribute to maximise the utility and the cost-benefit ratio of the lower end, such as in the case of the relatively simple models used in SFT.

Figure 2.5 A conceptual representation of the evolution of the cost-benefit ratio for unmanned aircraft prototypes: On the one hand, utility and complexity behave as in typical simulation models [56]. On the other, new technological developments, such as low-cost microprocessors and solid-state sensors, contribute to improving the cost-benefit ratio, an effect that is especially noticeable on the relatively simple prototypes.

3

Scaling Methods

The idea that two objects with different physical attributes, such as size, would respond differently to the same environment seems quite intuitive. Experiments with scaled test-articles are rarely expected to directly reveal the desired full-size characteristics, but to produce a set of data from which the desired full-scale characteristics can be estimated. A deep understanding of the phenomenon of interest and the physical laws behind it are essential for an appropriate design of the experiment. This chapter discusses the similarity principles that govern the most common scaling methods from a practical perspective.

3.1 Similarity Principles

In the interest of clarity, it seems appropriate to begin the discussion by defining some important concepts.

Model As stated in Section 2.2, the term *model* is predominantly used here to designate a physical representation of a true object, generally of a different size but interconnected by some type of similarity.

Similarity Furthermore, the concept of *similarity* or *similitude* represents in this context an equivalence of properties and behaviour between two systems that are described by the same physics, but that are not necessarily operating in the same conditions. *Similarity* is thus a condition that depends on the nature of the physical phenomenon of interest and that can be defined via dimensional analysis [57]. At a high level, there are typically three types of physical similarity with meaningful applications in engineering:

- *geometric similarity*, which implies equivalence in shape and proportions;
- *kinematic similarity*, which implies equivalence in motion;

- and *dynamic similarity*, which implies equivalence in motion and forces.

Within aircraft design, the first two types are typically used for communication and knowledge exchange. Examples of such uses are technical drawings, 3D-visualisation tools, and the interface of a Computer-Aided Design (CAD) environment. Nevertheless, the quantitative analysis of behaviour and performance of an aircraft involves the synthesis of multiple forces and motions, and therefore dynamic similarity is generally required for such studies. This is the case of aerodynamics, flight mechanics, and propulsion, among other disciplines.

Scale factor The word *scale* or *scale factor* is generally used in this context to represent the proportional ratio of linear dimensions of the model to the corresponding characteristics of the original object, i.e. it refers commonly to the correlation of characteristic physical dimensions assuming geometric similarity:

$$\frac{l_{model}}{l_{full-scale}} = scale\ factor \quad (3.1)$$

In engineering applications, and particularly in aeronautics, the scale factor of physical models used for research and development is often less than the unity, meaning that the model is smaller than the original object being studied. In this case, the term *subscale* is commonly applied. Figure 3.1 is a simple example of geometric similarity in which each model presents a different scale factor.

Figure 3.1 A traditional Russian *Matryoshka* doll: an example of *geometric similarity* in which the various models present different *scale factors*.

3.1.1 General Similarity Requirements

The motion, forces and conditions experienced by a full-size aircraft during flight can rarely be matched by a test article that is often several times smaller and that often operates in a different environment. In fact, the need to compare the magnitude of a given property between objects of different scale or characteristics is a recurrent problem in engineering. *Non-dimensional* or *dimensionless parameters*, which are derived from dimensional analysis, can be used in such cases to ensure that the dependence between the different physical quantities involved in the experiment is equal for the subscale and full-scale articles [57]. The number of non-dimensional parameters required to define these dependences for given phenomenon can be expressed as:

$$\left(\begin{array}{c} \text{Nr. nondimensional} \\ \text{parameters} \end{array} \right) = \left(\begin{array}{c} \text{Nr. physical} \\ \text{quantities} \end{array} \right) - \left(\begin{array}{c} \text{Nr. fundamental} \\ \text{units} \end{array} \right) \quad (3.2)$$

Conforming to dimensional analysis, complete similarity for a specific phenomenon can only be achieved by fulfilling all the conditions defined by all the non-dimensional parameters. In practical applications, however, these conditions can be often reduced to the most relevant parameters and disregard those who have little effect on the case of interest [6].

The set of non-dimensional parameters that govern a scaling problem are commonly referred to as *similarity parameters*, *scaling parameters*, or more generally *scaling laws*. Thus, these parameters or *laws* are problem-specific and can be derived for virtually any physical phenomenon. The derivation of similarity parameters relevant for flight applications is extensively discussed in references [6] and [58]. Therefore, only a brief overview of the most common cases will be given here.

According to the physics of flight, the forces and moments experienced by an aircraft in flight are generally a function of the aircraft and fluid properties, the characteristics of the motion, and gravitational effects:

$$F, M = f \left(\underbrace{\rho, \mu, c}_{\text{fluid prop.}}, \underbrace{l, \delta, m, I, EI', GJ'}_{\text{aircraft prop.}}, \underbrace{\alpha', V, a, \Omega, \dot{\Omega}, \omega}_{\text{motion charact.}}, \underbrace{g, t}_{\text{gravity, time}} \right) \quad (3.3)$$

All these seventeen physical quantities involve three fundamental units (*mass*, *length*, and *time*), which according to Equation (3.2), leads to fourteen different non-dimensional parameters defining similarity for flight dynamics. Following the dimensional analysis done in [6], these parameters take the form:

$$C_F, C_M = f \left(\begin{array}{cccccccccccccccc} \text{(a)} & \text{(b)} & \text{(c)} & \text{(d)} & \text{(e)} & \text{(f)} & \text{(g)} & \text{(h)} & \text{(i)} & \text{(j)} & \text{(k)} & \text{(l)} & \text{(m)} & \text{(n)} \\ \frac{\rho V l}{\mu}, \frac{V}{c}, \delta, \frac{m}{\rho l^3}, \frac{I}{\rho l^5}, \frac{EI'}{\rho V^2 l^4}, \frac{GJ'}{\rho V^2 l^4}, \alpha', \frac{a l}{V^2}, \frac{\Omega l}{V}, \frac{\dot{\Omega} l^2}{V^2}, \frac{\omega l}{V}, \frac{V^2}{l g}, \frac{t V}{l} \end{array} \right) \quad (3.4)$$

where C_F and C_M are now also non-dimensional aerodynamic coefficients in the usual form of $\left(\frac{F}{(1/2)\rho V^2 l^2}\right)$ and $\left(\frac{M}{(1/2)\rho V^2 l^3}\right)$ respectively.

The similarity parameters from Equation (3.4) are described as it follows:

- (a) *Reynolds number*: $Re = f\left(\frac{\text{Fluid inertial force}}{\text{Fluid viscous force}}\right) = \frac{\rho V l}{\mu} = \frac{V l}{\nu}$
- (b) *Mach number*: $M = f\left(\frac{\text{Fluid inertial force}}{\text{Fluid pressure (elastic) force}}\right) = \frac{V}{c}$
- (c) Control surface angular deflection: $\delta_a, \delta_e, \delta_r, \dots$
- (d) Relative density or mass ratio: $f\left(\frac{\text{Vehicle weight force}}{\text{Aerodynamic force}}\right) = \frac{m}{\rho l^3} = \frac{W}{\rho g l^3}$
- (e) Relative mass moment of inertia: $f\left(\frac{\text{Vehicle inertial force}}{\text{Aerodynamic force}}\right) = \frac{I}{\rho l^5}$
- (f) Aeroelastic-bending parameter: $f\left(\frac{\text{Bending force}}{\text{Aerodynamic force}}\right) = \frac{EI'}{\rho V^2 l^4}$
- (g) Aeroelastic-torsion parameter: $f\left(\frac{\text{Torsion force}}{\text{Aerodynamic force}}\right) = \frac{GJ'}{\rho V^2 l^4}$
- (h) Aircraft attitude relative to the airstream: α, β
- (i) Reduced linear acceleration: $\frac{al}{V^2}$
- (j) Reduced angular velocity: $\frac{\Omega l}{V}$
- (k) Reduced angular acceleration: $\frac{\dot{\Omega} l^2}{V^2}$
- (l) Reduced oscillatory frequency (*Strouhal number*): $\frac{\omega l}{V}$
- (m) *Froude number*: $Fr = f\left(\frac{\text{Inertial force}}{\text{Gravitational force}}\right) = \frac{V^2}{lg}$
- (n) Reduced-time parameter: $\tau = \frac{tV}{l}$

In order to achieve complete dynamic similarity for the aerodynamic coefficients and their respective derivatives it would be necessary to design an experiment in which all these parameters are equal in both model and full-scale aircraft, i.e. $(parameter_m)/(parameter_{fs}) = 1$ for all the terms detailed above. As a consequence of the diversity of requirements and our technological limitations (for example, we cannot modify the gravitational field), it is generally impossible to satisfy all the similarity requirements at once [5, 6, 58].

A deep understanding of the phenomena of interest is thus fundamental to carrying out meaningful subscale tests: It is fundamental to identify the most relevant similarity parameters for each individual case and, consequently, to design a specific subscale test that fulfils those specific requirements. A particular approach to similarity and all the considerations around a specific scaled experiment are commonly grouped under the term *scaling method*.

3.1.2 Common Scaling Methods

Most of the subscale experiments performed in aircraft research and development could be generally categorised into four different *scaling methods* according to their main focus and the degree to what they fulfil similarity conditions:

- **Aerodynamic scaling:** focus is exclusively on the similarity of the flow field, disregarding similarity of the aircraft self-motion.
- **Dynamic scaling:** focus is on the similarity of the rigid aircraft motion as well as the aerodynamic loads that cause it.
- **Aeroelastic scaling:** similar to dynamic scaling but including a focus on the similarity of vehicle deformations produced by aerodynamic loads.
- **Demonstrative scaling:** focus on the demonstration of technology in a relevant yet not fully developed state, and not necessarily following physical similarity conditions.

This classification is, to some extent, equivocal. The boundaries are not always obvious since many of the involved phenomena are closely interrelated, and therefore, some cases might fall partially in between or even outside these categories. In contrast to the three first, the term *demonstrative scaling* is not a familiar designation. In fact, such a term is proposed here to differentiate and categorise appropriately certain scaling methodologies that do not fit into the other categories. The following sections explore in more detail what are the characteristics and issues of each one of these four scaling methodologies.

3.2 Aerodynamic Scaling

The complexity of aircraft geometries and the innate nonlinearity of the flow-governing Navier-Stokes equations have traditionally forced aerodynamicists to rely heavily on empirical experiments to acquire information and to verify their estimations.

The ultimate goal of an aerodynamic study with subscale articles is generally to estimate the properties of the equivalent, real-world, flow-field around the full-scale vehicle. Therefore, the focus is here exclusively on the flow dynamics for a given set of conditions and a particular state of the vehicle. Thus, it is possible to disregard the vehicle motion and to transform the original problem into a flow-similarity problem. For instance, to study the flow around the wing at a specific attitude it is not necessary to take into account the mass properties of the aircraft. Although this approach may seem most appropriate for static tests, dynamic tests are also possible by, for example, inducing flow curvature and rotating or oscillating models.

Two major side effects come from disregarding vehicle dynamics: first, models are assumed to be rigid, or at least, to be in a static deformation state. Thus, the *real* aerodynamics resulting from the interaction between flow and aircraft structure would not be identified in the experiment. Second, the only way of conducting these experiments is by externally forcing the model to hold the desired attitude, since freedom of movement would produce dissimilar responses. This can be achieved by mounting the model on static or dynamic test rigs inside a closed test section, as in wind tunnels [9]; or in the open atmosphere, as in car-top testing [37]. Using this scaling method in Subscale Flight Testing (SFT) is therefore difficult and it would require additional means (for example, thrust vectoring) to force a free-flying model into the desired motion. Nevertheless, aerodynamic scaling is probably the most widely established scaling method in aircraft development and its use in wind tunnels is extensively covered in the literature.

Wind tunnels: a typical example of aerodynamic scaling

Historically, wind tunnel testing has been one of the main sources of information for technological aerodynamics and aeronautical applications [2]. Mounting subscale or even full-scale models inside tunnels where the moving-flow properties can be modified is a way of enabling designers to study flow behaviour in a laboratory environment. A general description of this method can be found in [55].

As a result of the progress in computational capability and numerical simulation, as well as the high costs of operating such complex facilities, the role of wind tunnel testing is changing: in many cases, its function is progressively shifting from a primary estimation tool to a source of calibration and verification for numerical simulations, which are instead used as the primary estimation method [2]. In addition, traditional wind-tunnel testing cannot always meet

all of the requirements of modern aeronautical research and development: On the one hand, internal testing rigs often have limited degrees of freedom and constrain the analysis of dynamic phenomena and unconventional manoeuvres. On the other hand, achieving appropriate flow conditions to cover the extensive flight envelope of modern aircraft requires very specialised facilities. Additionally, the similarity parameters often prescribe conditions that, depending on the scale factor and reference state, are very difficult to balance. This issue becomes even more challenging for tests in an open environment, such as in open-section wind tunnels and car-top testing, since it is generally impossible to manipulate the atmospheric conditions and the flow properties.

3.2.1 Aerodynamic Scaling Parameters

In order to achieve similar aerodynamic force and moment coefficients, the flow field around the subscale model should be equivalent to that of the full-scale counterpart. Note that, although it is commonly assumed that this implies an accurate geometric similarity between the two articles, this is not necessarily required as long as the flow field produced is equivalent. To identify the pertinent scaling parameters it is necessary to take a step back and perform a dimensional analysis as described in Section 3.1.1, although in this case, focusing on the equations of motion of the fluid.

The Navier-Stokes equations indicate that fluid motion is primarily governed by viscous, pressure, inertial, and gravity forces. For a compressible fluid, this will lead to the following similarity parameters already obtained in Equation (3.4): terms (a), (b), and (m) for static tests; and also terms (j), (l), and (n) for dynamic flow tests. Observe that if the flow is incompressible, the term accounting for the ratio between pressure and inertial forces (b) will take a slightly different form: the *Euler number* will be used instead of the *Mach number* [58].

An additional similarity parameter, known as the *Weber number*, will appear if surface-tension forces are considered [58].

Furthermore, the laws of thermodynamics introduce two other similarity parameters, known as the *Prandtl number* and the *Grashof number*. These parameters account for the ratio of momentum-diffusivity to thermal-diffusivity and the ratio of buoyancy to viscous force, respectively. In low-atmospheric flight at low speeds the Prandtl number is usually equivalent for both full-scale and subscale conditions, given that the fluid in which they operate has the same ratio of specific heats. Although the Grashof number is usually not comparable, the effects it accounts for are negligible in most of the practical applications considered here [58].

Lastly, the external characteristics of the aircraft as well as its attitude relative to the flow also need to be considered, which leads to the similarity parameters (c) and (h) from Equation (3.4).

As a result, the general similarity requirements for such an experiment could

be expressed as:

$$C_F, C_M = f \left(\overset{(a)}{\frac{\rho V l}{\mu}}, \overset{(b)}{\frac{V}{c}}, \overset{(b^*)}{\frac{\bar{p}}{\rho V^2 l^2}}, \overset{(c)}{\delta}, \overset{(h)}{\alpha'}, \overset{(j)}{\frac{\Omega l}{V}}, \overset{(l)}{\frac{\omega l}{V}}, \overset{(m)}{\frac{V^2}{lg}}, \overset{(n)}{\frac{tV}{l}}, \overset{(o)}{\frac{\sigma}{\rho V^2 l}} \right) \quad (3.5)$$

where the terms that need further explanation are:

(b) For compressible flow: *Mach number*, as defined in Section 3.1.1

(b*) For incompressible flow: *Euler number* = $f \left(\frac{\text{Fluid pressure force}}{\text{Fluid inertial force}} \right) = \frac{\bar{p}}{\rho V^2 l^2}$

(m) *Froude number*: $Fr = f \left(\frac{\text{Fluid inertial force}}{\text{Gravitational force}} \right) = \frac{V^2}{lg}$

(o) *Webber number* = $f \left(\frac{\text{Fluid surface-tension force}}{\text{Fluid inertial force}} \right) = \frac{\sigma}{\rho V^2 l}$

The term (b) or Mach number relates to the pressure differential across shock waves and should only be used in compressible flow. It can be substituted by the term (b*) or Euler number in cases of incompressible flow, although this would only be necessary for problems in which the similarity of the pressure field is important, such as when the body forces are determined from measurements of pressure distribution. In other cases, this similarity parameter (b*) can normally be neglected [58].

Moreover, it should be observed that the term (m) or Froude number accounts now for the gravitational effect on the fluid and not on the vehicle. Considering that the effect of gravitation on the airflow is minimal, this parameter can also be disregarded in most cases [58].

According to these assumptions, the relevant similarity parameters for aerodynamic scaling can be reduced to:

$$C_F, C_M = f \left(\underbrace{\overset{(a)}{\frac{\rho V l}{\mu}}, \overset{(b)}{\frac{V}{c}}, \overset{(c)}{\delta}, \overset{(h)}{\alpha'}}_{\text{static tests}}, \underbrace{\overset{(j)}{\frac{\Omega l}{V}}, \overset{(l)}{\frac{\omega l}{V}}, \overset{(n)}{\frac{tV}{l}}}_{\text{dynamic tests}} \right) \quad (3.6)$$

Despite these simplifications, satisfying all the aerodynamic scaling parameters at the same time is in most cases infeasible; as mentioned in wind-tunnel testing literature [2, 55, 58, 59]. This problem becomes even more significant in open test-sections and free-flight testing since flow properties such as chemical composition, pressure, and temperature, cannot be modified as it is done in advanced wind-tunnel facilities. In most of the practical applications discussed

here, the main obstacles to achieving flow similarity are those involving viscous and pressure forces, i.e. Reynolds number (a) and Mach number (b).

Fortunately, in many cases the impact of these two parameters can be studied independently, considering that Reynolds number effects are typically negligible outside the boundary-layer region near the body surface [55, 58, 59, 60]. Experimental studies such as [61] and [62] support this assumption by showing a clear distinction between the effect of Mach number and those caused by Reynolds number variations. This assumption is valid for subsonic and supersonic flow for Mach numbers less than approximately 5, a point at which the shock waves start interacting extensively with the boundary layer and hence, Mach number effects couple to viscous effects [6].

3.2.2 Scale Effects

For certain experiments in subscale conditions, it could be infeasible, impractical, or eventually unnecessary to achieve complete flow similarity by satisfying all the scaling parameters. Dissimilarity in one or more of these parameters normally causes deviations from the full-scale results which are usually known as *scale effects*. The significance of these scale effects and the degree of uncertainty that they introduce varies greatly from case to case.

In fact, despite the inevitable exposure to undesirable scale effects, only a very small fraction of experimental aerodynamics testing is conducted at representative, full-scale Reynolds and Mach numbers due to the high cost involved and the few operative ground facilities with the necessary capabilities [60]. It is therefore essential to understand and quantify the influence of scale effects in order to apply the necessary corrections; a complex task that often requires not only extensive knowledge and experience but also complementary data from other tests or methodologies [63].

In the context of vehicle aerodynamics and hydrodynamics, Barlow states that the understanding of scale effects consists mainly on the understanding of boundary layer properties and behaviour as they are affected by differences in the model and full-scale articles [55]. According to this author, even scale effects observed in flow wakes can, in most cases, be explained by changes in the boundary layer.

The role of Reynolds number

Flow aspects such as the boundary layer are very sensitive to variations in Reynolds number [60]. While it is clear that this parameter plays a significant role, scale effects of relevance for aerodynamics are not limited to a single Reynolds number problem. This issue has been extensively discussed in wind tunnel literature. For instance, according to Haines [59], scale effects that are often mixed with Reynolds number effects can be classified into three categories:

- “Scale effects”: term used by Haines to describe effects not depend-

ent on Reynolds number, but related to the scale model. These often include geometric similarity issues, such as model geometric fidelity and aeroelastic distortion.

- **Pseudo-Reynolds number effects:** effects that at first may be wrongly identified as Reynolds number effect, but ultimately dependent on other variables. Such effects could be introduced by an inadequate testing methodology, data processing errors, and by the influence of other variables that are not considered or known at the time of testing.
- **Reynolds number effects:** effects directly or indirectly dependent on Reynolds number. Direct Reynolds number effects involve intrinsic boundary layer properties, such as laminar-turbulent transition, separation from the surface, shock wave interaction with the boundary layer, and velocity inside it; and affect parameters like the viscous drag, and location of boundary layer separation. Indirect Reynolds number effects are those induced by the intrinsic characteristics of the boundary layer, such as effects on shock strength and location, and effects on the overall circulation and pressure distribution; which are reflected in parameters like lift, pitching moment, drag, stall characteristics, and buffeting.

The interaction between all these effects is fairly complex and, in some cases, the role of Reynolds number cannot be totally clarified until the full-scale article is tested. The behaviour and magnitude of such scaling effects are often case-specific and generally unpredictable. In fact, experiments have occasionally shown counterintuitive results. In the investigation carried out by Banks et al. [64], wind tunnel data from large-scale low Reynolds number tests predicted the high-angle-of-attack flight characteristics of an F/A-18 fighter better than similar data from small-scale higher Reynolds number tests. In this case, the absolute geometric fidelity of the full-scale airframe used in the low Reynolds number test was more relevant for the forebody flow topology than the larger difference in Reynolds number.

As a consequence of the lack of general rules, extrapolation of results from lower Reynolds number data is largely based on the knowledge and experience of the aerodynamicist. Aerospace manufacturers often base Reynolds number corrections on empirical databases accumulated from years of experience with different programmes; a highly valuable information which usually remains company proprietary. This method produces reliable estimations for conventional or well-understood configurations but introduces a considerable uncertainty in cases where the configuration is not well understood or the flow is highly complex [2, 55, 60]. Nowadays, complementary analysis tools such as Computational Fluid Dynamics (CFD) are also used to estimate scale effects in experimental data. According to Petterson et al.: “*Today, CFD methods are commonly used to predict flow features at Reynolds numbers higher than what the aircraft model is subject to in the wind tunnel, and at higher Reynolds number than the turbulence model has been calibrated to*” [65].

Because of their effects on the boundary layer, Reynolds number variations have a strong impact on the flow topology and forces produced across bodies for which there is no geometrically fixed separation, such as smooth and curved surfaces [55, 60]. Under these circumstances, extrapolating results obtained at one value of Reynolds number to a higher value could be misleading. According to Munro [60], even interpolation must be performed cautiously if the flow is specially Reynolds-number-sensitive since it might present rapid changes in topology; a phenomenon that is usually observed across the transitional region where many typical wind tunnel experiments are performed. A common technique to simulate flow conditions expected at a Reynolds number higher than the number achieved in the test is to artificially fix the laminar-turbulent transition and the separation at a predefined location by means of grit, strips and other flow-tripping devices [6, 55].

For flow around sharp corners, however, the separation is usually fixed at the edge and the flow often presents little or no dependence on Reynolds number. This kind of sharp features is commonly found in modern combat aircraft with large flight envelope and stealth capabilities. For instance, many contemporary fighters feature chined forebodies and highly swept lifting surfaces for controlled radar reflectivity, high-speed performance, and high AOA excursions. The GFF configuration, shown in Figure 3.2, is a good example of these characteristics. The aerodynamics of such a configuration at high AOA are dominated by separated flow and vortex structures. Although the boundary layer region prior to separation is strongly dependent on Reynolds number, both the vortex sheet and the inviscid outer flow region remain relatively insensitive to Reynolds number variations [60]. Furthermore, the literature is in general agreement that, in sharp and highly swept surfaces, the separation location, trajectory and breakdown of the primary vortices is mainly determined by the geometry and the angles of attack and sideslip. Consequently, configurations with these characteristics are especially well suited for experiments with subscale models in which Reynolds number similarity cannot be maintained.

Even for more conventional configurations, it is still possible to study certain aerodynamic characteristics without a severe influence of scale effects caused by Reynolds number dissimilarity. For instance, according to Barlow, the rate of change of drag with lift, usually considered as the change in *span efficiency* or *Oswald factor* e , typically does not change with Reynolds number for straight wings [55]. This author explains that the slope of the nearly-straight line resulting from a plot of C_L^2 versus the total drag coefficient C_D is practically independent of Reynolds number, although its position moves according to the scale effects on the parasite drag coefficient C_D . Accordingly, a subscale test with Reynolds number dissimilarity could still be used to estimate the full-scale e by completing the following equation, as in [55]:

$$e = \frac{1}{(dC_D/dC_L^2)\pi AR} \quad (3.7)$$

Figure 3.2 Aerodynamic phenomena in which the flow transition and detachment are fixed by geometric features can be well-suited for experiments in subscale conditions with dissimilar Reynolds number. The image shows an example of such phenomena, in which profiles of detached flow on the sharp-cornered Generic Future Fighter (GFF) configuration have been obtained from CFD computations. Courtesy of Jörg Schminder, Linköping University.

The role of Mach number

There seems to be a clear agreement in the literature on that the Mach number has a significant influence in the flow characteristics as soon as compressibility effects begin to be significant, and this may happen even far below the transonic regime. Wolowicz et al. [6] state that the differences in true and incompressible-flow dynamic pressure and temperature may be significant for Mach numbers in excess of 0.20, while other sources often extend this limit to Mach number 0.3. It must be noted that even in a flow with low free-stream Mach number, compressibility effects may be significant in local flow around certain geometries. For instance, the studies on the F/A-18 fighter configuration reviewed by Erickson et al. [66] revealed that the flow around some components such as the leading-edge extensions or *LEX* present Mach number effects at Mach numbers as low as 0.15 – 0.25.

Mach number effects can be isolated from other scale effects for subsonic and supersonic flows until reaching a Mach number of approximately 5, the point at which the shock waves start interacting extensively with the boundary layer and hence, Mach number effects couple to viscous effects [6].

Differently from the cases in which a Reynolds number mismatch can be moderated by means of active boundary-layer control, there are no effective techniques to artificially compensate for Mach number dissimilarity. In fact, according to Rolston [67], the importance of matching the full-scale, free-flight

Mach number during wind tunnel tests has historically never been in question. The need for achieving full Mach number similarity is, therefore, an important limitation for any kind of subscale tests in which compressible flow is to be studied.

3.2.3 Practical Limitations

Scale effects introduce important limitations for the design and execution of SFT experiments. Table 3.1 presents four different aircraft concepts that will be used here to visualise and discuss the main practical limitations associated with each scaling method. These concepts cover an extensive design space and each one of them corresponds to a subscale demonstrator manufactured at Linköping University.

Table 3.1 Four different aircraft concepts used to visualise the impact of the scaling parameters under different circumstances. For each one of these concepts, there is a subscale model developed at Linköping University. Data in this table corresponds to the design parameters of the full-scale vehicle.

Picture
Identifier	(a)	(b)	(c)	(d)
Aircraft type	Generic Future Fighter (GFF)	Light business jet	Light-Sport Aircraft (LSA)	Human-Powered Aircraft (HPA)
Take-off mass	15400 kg	4000 kg	290 kg	100 kg
Wingspan	11 m	14 m	5 m	25 m
Cruise speed	300 m s^{-1}	160 m s^{-1}	50 m s^{-1}	8 m s^{-1}
Cruise altitude	9000 m	11000 m	3000 m	5 m

As discussed earlier, one of the main challenges for aerodynamic scaling in SFT is the Reynolds number similarity: full-scale Reynolds number can rarely be achieved if the scale factor is far from the unity. Figure 3.3 shows this problem on the four aircraft types introduced in Table 3.1 by comparing the chord Reynolds number achieved with different scaled models and testing techniques with that expected during full-scale design conditions. Although a higher-than-test Reynolds number can, in some cases, be simulated by controlling the boundary layer behaviour, in most cases the scale effects derived from this dissimilarity should be taken into account. The magnitude of dissimilarity and the significance of the consequent Reynolds number effects differ from case to

case. For example, the discrepancies related to Reynolds number effects on lifting surfaces between model and full-scale may be expected to be larger in the case (c) than in the case (a): In spite of being apart by less than one order of magnitude in terms of chord Reynolds number, the vehicles of case (c) within a regime where boundary-layer transition typically occurs and where significant changes in flow topology may be expected [68]. Additionally, the rounded geometry of (c) is likely more sensitive to these changes than the sharp-edged configuration (a).

Figure 3.3 Reynolds number obtained at the mean chord of the main wing for models of different scale using various testing techniques at sea level, compared to that expected on the full-scale vehicle during nominal operation. The four different cases correspond to the configurations described in Table 3.1.

The other major challenge for aerodynamic scaling with subscale models in the open atmosphere is reproducing the compressibility effects by achieving Mach number similarity. As discussed earlier, this is essential for cases in which the full-scale phenomenon of interest involves compressible flow. Differently from the Reynolds number, the maximum Mach number attainable during SFT is not directly related to the scale factor of the model. Instead, it is a consequence of the structural design of the model and its propulsion system, as well as the testing technique used and the maximum flight speed at which the model can be safely controlled. Figure 3.4 shows a practical example in

which the Mach number achieved during testing of various subscale models is compared to the expected Mach number range of the full-scale vehicles. As it can be seen in this figure, it is sometimes possible to neglect compressibility effects (green area) while in others it is only possible to study the low-end of the full-scale flight envelope with the subscale model without introducing uncertainties due to compressibility effects (yellow area and beyond).

Figure 3.4 Mach number at which various subscale models are tested in the open atmosphere, compared to the Mach number range where the full-scale vehicles would be operated. The four different cases correspond to the configurations described in Table 3.1, and the background colours represent incompressible (green), risk for compressibility (yellow), and compressible (red) flow regimes.

Another aspect that needs to be taken into consideration is the geometrical distortion introduced by the additional systems and features needed to make the subscale model a functional flying vehicle. Examples of this distortion are external control-surface links, differences in the installed propulsion and intake ducts, access panels, antennas, differences in the landing gear arrangement, minor geometrical simplifications, and other similar elements. In addition, the integration of external instruments such as probes, vanes, and cameras may also be inconsistent with the full-scale geometry. Furthermore, the deformation of the airframe under load may also contribute to the dissimilarity: unless particular considerations are taken into account during design and manufacturing, the structural stiffness of the model would be generally different from the equivalent stiffness of the full-scale aircraft, a factor that may introduce

additional geometrical distortion and, therefore, deviations in the measured aerodynamic parameters.

These and other concerns for aerodynamic scaling are summarised in Table 3.2. This table synthesises all the previous discussions and presents a list of the main practical issues and considerations of importance for aerodynamic scaling of subscale models in the open atmosphere.

Table 3.2 *Summary of the main concerns and issues regarding aerodynamic scaling for subscale free-flight models tested in the open atmosphere.*

	Issue	Discussed in
1	Aerodynamic scaling with free-flight models that are not dynamically scaled may be impractical: since vehicle dynamics are dissimilar, attitude and motion must be externally enforced by actively controlling either the vehicle or the flow.	[6]
2	Reynolds number similarity is generally unattainable using models with a scale factor far from the unity: related scale effects may be significant, and studies may need to be limited to phenomena insensitive to Reynolds number.	[2, 6, 55, 58, 60, 61, 66, 67]
3	For compressible flow, Mach number similarity may only be attainable for low-speed subsonic flow due to vehicle and operational constraints.	[6, 55, 58, 60, 61, 66, 67]
4	Model geometrical distortion: fidelity, actuation of control surfaces, propulsion system differences.	[2]
5	Model geometrical distortion: dissimilar aeroelastic deformation.	[2, 6]
6	Distortion introduced by the instrumentation: effects on the flow and on the measurements.	[2]

It can be concluded that one of the most important aspects regarding aerodynamic scaling is that it requires an extensive comprehension of the flow prior to the design of the subscale experiment. As seen before, only a reduced number of flow problems can be explored with free-flight subscale models without accounting for undesired scale effects, and even in those cases, it may be difficult to achieve the right test conditions using non-dynamically scaled models. As a result, *pure* aerodynamic scaling is usually inappropriate for SFT, although it may be convenient for other methods such as car-top testing.

3.3 Dynamic Scaling

In many cases, the research focus is not only on the aerodynamic forces acting on the aircraft but also on the motion that they induce. While there are some well-established methods to estimate static characteristics of an aircraft, such as static aerodynamic coefficients, the determination of dynamic characteristics presents more difficulties. As shown in Figure 3.5, there are no analytical methods that provide medium or high fidelity predictions of dynamic behaviour. While numerical methods such as CFD are making rapid progress in this area, wind-tunnel and flight testing still remain essential for uncertainty reduction.

Figure 3.5 *Nature of different methods commonly used to investigate the static and dynamic behaviour of an aircraft at a medium/high fidelity level.*

Nevertheless, the study of dynamics in wind or water tunnels is generally difficult: The model support, the wall effects, and the size of the test section limit severely the degrees of freedom and the types of motion that can be performed. Since real flight testing is generally not an option during the early stages of design, the uncertainty in dynamic behaviour has to be dealt with using alternative solutions. Historically, one of these solutions has been testing free-flight subscale models in the open atmosphere as well as inside sufficiently large wind tunnels [5, 6, 9], as introduced in Section 1.1. In this case, the vehicle is not held rigidly and it is free to develop its own motion. Consequently, the similarity principles have to be fulfilled not only for the aerodynamic forces but also for the vehicle motion.

3.3.1 Dynamic Scaling Parameters

While the similarity was limited only to the flow field in aerodynamic scaling, dynamic scaling also requires similarity for the vehicle motion.

According to the general similarity principles derived in Section 3.1.1, the similarity in flight dynamics is governed by the parameters given in Equation (3.4). The parameters that refer to flow similarity are here needed to ensure similar aerodynamic forces, as in Equation (3.6). The additional parameters that account for all the aspects of the vehicle motion, $(h, \dots, n)$, are also compulsory. The only simplification that can be made is to assume a rigid

vehicle and hence leaving aside those parameters that account for an elastic airframe, i.e. terms (f) and (g). By considering a rigid vehicle, any aeroelastic effects are either neglected or accounted for by other means. As a result, the relevant similarity parameters for dynamic scaling can be reduced to:

$$C_F, C_M = f \left(\overset{(a)}{\frac{\rho V l}{\mu}}, \overset{(b)}{\frac{V}{c}}, \overset{(c)}{\delta}, \overset{(d)}{\frac{m}{\rho l^3}}, \overset{(e)}{\frac{I}{\rho l^5}}, \overset{(h)}{\alpha'}, \overset{(i)}{\frac{a l}{V^2}}, \overset{(j)}{\frac{\Omega l}{V}}, \overset{(k)}{\frac{\dot{\Omega} l^2}{V^2}}, \overset{(l)}{\frac{\omega l}{V}}, \overset{(m)}{\frac{V^2}{l g}}, \overset{(n)}{\frac{t V}{l}} \right) \quad (3.8)$$

where C_F and C_M are non-dimensional aerodynamic coefficients in the usual non-dimensional form, and all the other terms have been previously described in Section 3.1.1. It is noteworthy that the term (m), or Froude number, accounts here for the vehicle inertial forces and not for the fluid inertial forces as in Equation (3.5).

It may be observed that the terms (d) and (e) prescribe that the mass distribution of the full- and subscale vehicles must be similar in order to obtain equivalent inertial force and equivalent rigid-body motion. Hence, the moments of inertia of the subscale vehicle must be proportional to those of the full-scale counterpart; a condition that can influence substantially the structural design of the subscale airframe and the experiment limitations.

Another observation is that, while in aerodynamic scaling the focus is on recreating the flow field, in the study of rigid-body dynamics it is generally enough to ensure that the resultant aerodynamic forces and moments acting on the body are similar at every state. Although it is usually assumed that such a condition requires precise geometrical similarity, this is not true. Geometrical or flow-field modifications would not affect the results as long as all the aerodynamic forces and moments, as well as the mass properties of the body, are ultimately similar. This fact may be an advantage when it comes to reproducing certain forces, loads, or states that cannot be easily achieved at subscale conditions.

But perhaps the major observation to be made about Equation (3.8) is the following: the terms (a), (b), and (m); i.e. the Reynolds, Mach, Froude numbers respectively; dictate contradictory requirements for the subscale model velocity. Even assuming a certain degree of Reynolds number dissimilarity, as seen in Section 3.2, the divergence of the Mach and Froude numbers remains problematic for SFT whenever flow compressibility is considered. Satisfying both similarity requirements at once would require an improbable change in the gravitational field. Once again, it is infeasible or impractical to fulfil simultaneously all similarity parameters: they need to be assessed and balanced during the design of the subscale experiment.

The disagreement between the similarity conditions prescribed by the terms (m) and (b) in Equation (3.8) generates two different subtypes of dynamic-scaling strategies: one that pursues complete Froude number similarity at the expense of dissimilar fluid-compressibility effects, and another that pursues

complete Mach number similarity at the expense of dissimilar proportions between inertial and gravitational effects. The first is commonly known as *Froude scaling* while the latter is commonly known as *Mach scaling* [6]. Froude number similarity can be met easily by tailoring the mass properties of the subscale model, and hence, Froude scaling is the natural choice for cases dealing with an incompressible flow or in which compressibility effects can be disregarded. On the contrary, Mach number similarity may be more difficult to meet for aircraft flying faster than the usual boundary for compressibility effects (see Section 3.2 and Figure 3.4), as the model velocity depends not only on its performance but also on eventual operating limitations.

3.3.2 Scale Effects

The exposure to undesired scale effects is, in this case, similar to that of the aerodynamic scaling method. Most of the discrepancies are introduced by the inability to achieve complete similarity for the aerodynamic forces and moments acting on the subscale vehicle.

To begin with, it is usually not possible to reach the required Reynolds number with a subscale model flying in natural atmospheric conditions: the large influence of the scale factor on this quantity (proportional to the characteristic length) cannot always be fully compensated by altering the flight speed and the flight altitude. In most cases, a certain degree of Reynolds number dissimilarity has to be accepted and accounted for, as discussed in Section 3.2.

Furthermore, the divergence between the similarity conditions for Froude and Mach number and the consequent choice of scaling strategy will introduce additional scale effects: If the experiment is scaled following Froude number similarity, the Mach number of the model will be lower than what it should be. Similarly, the Reynolds number of the model will be lower unless the full-scale vehicle is flying at high altitude. Figure 3.6 shows this trade-off for a Froude-scaled model flown at sea level.

A similar effect is found when the experiment is scaled following Mach number similarity: Although compressibility effects will be correct, the Froude number of the model will generally be higher than what it should, and its Reynolds number will be lower unless the full-scale vehicle is flying at high altitude. Figure 3.7 presents this alternative trade-off scenario.

The role of Froude number

The Froude number similarity applied to an aircraft accounts for an equivalent ratio between the inertial and gravitational effects during dynamic motion. Hence, a mismatch in this parameter will produce a dissimilar response during flight manoeuvres, such as the resulting load factor and bank angle during a constant-altitude banked turn, or the vehicle trajectory during a spin [6].

Nevertheless, the implications of Froude number similarity go beyond dynamic manoeuvring: even at steady and level flight, where the load factor is

Figure 3.6 Ratio of Reynolds number and ratio of Mach number for a subscale model tested at sea level with respect to those of a full-scale vehicle at different altitudes; according to dynamic scaling with Froude number similarity. Each line represents a different scale factor.

equal to one, important characteristics such as the lift coefficient are also dependent on the ratio between inertial and gravitational effects. In the case of the lift coefficient, a discrepancy in Froude number will cause the model to find the equivalent equilibrium of forces at a different AOA than that of the full-scale aircraft.

3.3.3 Practical Limitations

Due to the need for similar aerodynamic forces and moments, dynamic scaling typically involves most of the practical issues mentioned earlier in Section 3.2. More specifically, the issues no. 2, 3, 4, 5, and 6 from Table 3.2 apply in the same terms to typical dynamic scaling experiments. Figures 3.3 and 3.4 illustrate the first two of these issues using the cases presented in Table 3.1 as examples.

Unfortunately, the requirements for similarity in mass and inertial characteristics introduce additional problems for the practical execution of subscale experiments. The similarity of mass ratio and mass moments of inertia, terms (d) and (e) in Equation (3.8), often prescribe model weights that differ significantly from those usually found in similar non-dynamically scaled models. If

Figure 3.7 Ratio of Reynolds number and ratio of Froude number for a subscale model tested at sea level with respect to those of a full-scale vehicle at different altitudes; according to dynamic scaling with Mach number similarity. Each line represents a different scale factor.

the aircraft is assumed to be a rigid body, the moments and products of inertia can easily be matched by distributing individual masses along the airframe; although this technique is only applicable if the airframe is initially lighter than the target weight. In fact, achieving the right inertial characteristics becomes rather challenging if the prescribed weight is lower than that resulting from a typical model manufacturing process: special materials or manufacturing techniques may be necessary and the inertia requirements may have a significant impact in the model design.

In some cases, the requirements for similarity in mass and inertial characteristics will directly make it impractical or infeasible to conduct a subscale experiment at certain scale factors. The different examples introduced in Table 3.1, plus two additional cases, are used in Figure 3.8 to illustrate this problem. In this figure, the background colours suggest the relative level of difficulty (and eventual cost) of performing SFT with instrumented, dynamically scaled models according to their take-off mass: low (green), medium (yellow), and high (red). For instance, the legal requirements for civil operation of this kind of vehicles in many European countries change significantly when the take-off mass exceeds 25 kg, and even more dramatically when it exceeds 150 kg. On the lower side, it becomes generally difficult to build and operate a functional

model of less than 1 kg of take-off mass including the necessary instrumentation. Figure 3.8 shows two lines for each case: the solid lines represent similarity to the full-scale vehicle at sea level while the dashed lines represent similarity to the full-scale vehicle when it flies at its design altitude. The GFF, indicated as (a), is a good example of the trade-off needed: in this case, the subscale model is usually operated below the required weight for dynamic similarity in order to avoid legal requirements of a heavier vehicle category, and hence, to lower significantly the operating costs.

Figure 3.8 Correlation between take-off mass and scale factor according to dynamic similarity for subscale testing at sea level. Background colours indicate different levels of cost according to the challenges of manufacturing and operating an instrumented model of the respective weight. For each of the cases, solid lines represent similarity to the full-scale vehicle at sea level while dashed lines represent similarity to the full-scale vehicle at its design altitude. In the case (a), the subscale model is flown lighter than prescribed for cost and feasibility reasons. Besides the aircraft described in Table 3.1, two complementary examples have been added: *(e) corresponds to NASA's AirSTAR Generic Transport Model (GTM-T2) [19]. **(f) corresponds to NASA-Boeing's BWB demonstrator (X-48B) [16].

Another potential problem for the design of dynamically scaled experiments is the decrease of actuation and response times. According to the similarity parameters in Equation (3.8), the magnitude of time in the model should decrease as the scale factor is also reduced. On the one hand, this affects the response time and makes the model motion quicker than that of the full-scale, as shown in Figure 3.9 (top) for the two types of dynamic scaling. Consequently, higher performance and faster sampling rates may be required from the instrumentation and the data acquisition system.

On the other hand, this effect also introduces higher demands on the control system: the speed at which the control surfaces are deflected should be increased accordingly to the time requirements. While the latency in the radio-control system is usually not a problem with modern equipment, the speed of proportional servo-actuators is much more limited and usually constitutes a bottleneck. In challenging cases in which proportional actuators with appropriate performance are not available, it might be necessary to utilise simpler, non-proportional (on-off) high-speed actuators, as tested by NASA in several small-scale models [5, 6]. Figure 3.9 (bottom) shows an example of how angular rates change according to the scale factor and type of dynamic scaling.

These practical limitations, together with other concerns discussed in previous sections, are summarised and presented in Table 3.3. Although this table contains by no means all the existing issues for dynamic scaling, it includes the most significant challenges for the design of subscale experiments using free-flight models in the open atmosphere.

Figure 3.9 Ratio of response time (top) and ratio of angular rates (bottom) for a subscale model tested at sea level with respect to those of the full-scale vehicle at any altitude (for dynamic scaling with Froude number similarity), and at two given altitudes (for dynamic scaling with Mach number similarity).

Table 3.3 *Summary of the main concerns and issues regarding dynamic scaling for subscale free-flight models tested in the open atmosphere.*

	Issue	Discussed in
1	Similarity of aerodynamic forces and moments introduces issues no. 2, 3, 4, 5, and 6 from Table 3.2.	Section 3.2
2	Generally not possible to achieve Froude and Mach number similarity simultaneously: one of these two parameters has to be prioritised.	[5, 6]
3	Similarity of mass ratio and moments of inertia may require models that are either too light or too heavy to be produced and operated economically. Depending on the type of aircraft, only a reduced range of scales may be of practical use.	[5, 6, 69]
4	Mass and inertia characteristics might vary differently in subscale and full-scale vehicles during flight due to different fuel fractions and fuel system architecture.	
5	Deviations introduced by dissimilar dynamics in control and actuation systems. Especially at small scales, control-surface actuators might not operate as quickly as required.	[5]
6	The quick angular motion of models with small-scale factors may require data acquisition systems with high logging frequencies, as well as it can make manual piloting difficult or infeasible.	[5]

As a consequence of all the above, it could be said that dynamic scaling builds on the similarity principles of aerodynamic scaling. A good knowledge of the phenomena of interest and the expected flow conditions are still essential, although this must be completed with a comprehensive evaluation of other variables related to the scaling of the vehicle itself: the feasibility of testing a dynamically scaled model at certain scale factor will in most cases be strongly influenced by the available resources for manufacturing and operation, as well as the characteristics of the available components and onboard systems, such as propulsion, control, and data acquisition systems.

3.4 Aeroelastic Scaling

In other types of scaling we have systematically assumed that both the subscale and full-scale vehicles behave as a rigid body. This assumption is usually appropriate for the study of static or pseudo-static characteristics of the aircraft, such as aerodynamic coefficients under certain conditions or performance at given points of the flight envelope. Moreover, steady states in which elastic airframe deformation is anticipated could also be studied in subscale conditions with rigid models that already incorporate the expected distortions. Nevertheless, neglecting the flexibility of the aircraft implies disregarding multiple dynamic phenomena that are increasingly relevant for aircraft conceptual design.

Although structural dynamics and flight dynamics were often studied separately in the past, the quest for performance optimisation in modern aircraft has led to an increasing use of light, more efficient, flexible structures in which these two disciplines are tightly coupled [70, 71]. The growing interest in studying and modelling these interactions during the early stages of aircraft design is also motivated by the development of optimum and adaptive flight control laws that take into account and utilise aeroelastic phenomena. Figure 3.10 is based on the *triangle of forces* conceived by Collar [70], and it graphically shows the interaction between the three main types of forces that define the aeroelasticity domain. Various phenomena are located on this triangle according to their relative dependence to the forces, although these couplings correspond only to a general definition and may be different for certain types of aircraft, conditions, and modelling approach.

The experimental validation of aeroelastic (mathematical or simulation) models and advanced control laws is a risky and generally expensive process due to the potentially catastrophic damage that some of these phenomena could cause to the aircraft integrity. There is, therefore, a big interest in finding alternative methods for evaluating these subjects as early as possible in the design process; and it is here where SFT can be an economical, low-risk alternative to full-scale flight and wind-tunnel testing. One of the best examples of this application is perhaps the *Drones for Aerodynamic and Structural Testing* (DAST) programme carried out by NASA from 1977 to 1983 [72, 73, 74]. During this programme, two *BQM-34 Firebee II* target drones were modified with supercritical aerofoils and new wing geometry, the *Aeroelastic Research Wing* (ARW). These vehicles were mainly utilised to evaluate active control systems and flutter suppression techniques, as well as for stability and structural investigations.

NASA's *AirSTAR Generic Transport Model* (GTM) has also been utilised for research on adaptive control and other advanced control laws [19, 75, 76, 77]; even though this subscale model was not scaled according to aeroelastic similarity and it is too stiff for the study of interactions between structural dynamics and control laws.

Figure 3.10 The “triangle of forces”, adapted from Collar [70], represents graphically the dynamic aeroelasticity domain and how different phenomena typically interact with its governing forces.

A recent example of an advanced subscale model specifically designed for the study of aeroelastic phenomena is the Lockheed Martin *X-56A* or *Multi-Utility Technology Testbed* (MUTT), a 15% scaled version of the *SC006A Sensorcraft* configuration with interchangeable wings [78, 79, 80]. This remotely piloted model was mainly designed to investigate the development and suppression of the unstable coupling between the short-period mode and the first symmetric wing mode, a phenomenon known as Body Freedom Flutter (BFF) which is commonly found in high aspect ratio wings [81]. This aeroelastic problem was also recently studied by Ouellette et al. using a much simpler remotely controlled model derived from a Commercial Off-The-Shelf (COTS) model aircraft [71, 82].

Another programme in which a remotely piloted model is used to study a similar aeroelastic phenomenon is the *Flutter-free Flight Envelope Extension for Economical Performance Improvement* (FLEXOP) research project [83, 84]. This European project, part of the *Horizon 2020* initiative, is currently ongoing and it involves several European universities and manufacturers.

3.4.1 Aeroelastic-Scaling Parameters

As hinted in Figure 3.10, a subscale experiment that aims to investigate dynamic aeroelasticity will necessarily involve elastic, inertial, and aerodynamic forces. Accordingly, similarity requirements for structural flexibility will add to those involved in dynamic scaling (Section 3.3), which already included those of aerodynamic scaling (Section 3.2).

Thus, for a general dynamic problem with a flexible aircraft, similar aerodynamic forces and moments can be obtained by satisfying all the similarity requirements initially included in Equation (3.4) which was obtained according to Wolowicz et al. [6]; i.e.:

$$C_F, C_M = f \left(\overset{(a)}{\frac{\rho V l}{\mu}}, \overset{(b)}{\frac{V}{c}}, \overset{(c)}{\delta}, \overset{(d)}{\frac{m}{\rho l^3}}, \overset{(e)}{\frac{I}{\rho l^5}}, \overset{(f)}{\frac{EI'}{\rho V^2 l^4}}, \overset{(g)}{\frac{GJ'}{\rho V^2 l^4}}, \overset{(h)}{\alpha'}, \overset{(i)}{\frac{al}{V^2}}, \overset{(j)}{\frac{\Omega l}{V}}, \overset{(k)}{\frac{\dot{\Omega} l^2}{V^2}}, \overset{(l)}{\frac{\omega l}{V}}, \overset{(m)}{\frac{V^2}{lg}}, \overset{(n)}{\frac{tV}{l}} \right) \quad (3.4)$$

This formulation includes the required elastic similarity between full- and subscale vehicles by means of the terms (f) and (g), which account for the aeroelastic bending and aeroelastic torsion, respectively. The other similarity parameters represent the same requirements as in dynamic scaling, although an important observation must be made: the requirements for similar mass moment of inertia characteristics imply, in this case, similarity in the actual mass distribution. In Section 3.3 it was said that, for a dynamically scaled rigid aircraft, similarity in mass moments and products of inertia could be met by adding the necessary masses on the airframe; however, aeroelastic scaling requires that the actual distribution of these masses is similar to that of the full-scale vehicle [6]. Even though this detail might not seem of much importance, it may add significant complexity to the design and manufacturing of the model.

Equation (3.4) is nevertheless a general formulation for complete similarity based on aerodynamic forces and moments that can rarely be fulfilled in practical applications. Specific aeroelastic problems usually demand applied formulations and partial similarity tailored to the phenomena of interest and the available testing possibilities. For instance, Ouellette et al. propose in [71] a more practical set of aeroelastic scaling laws applied to the study of couplings between the short-period mode and the wing structural dynamics, such as Body Freedom Flutter (BFF). Among other simplifications, these authors

argue that the sensitivity of the short-period mode to the Froude number is generally low and therefore the flight velocity can be lower than that prescribed by typical Froude scaling. The reduced set of similarity requirements allowed the development of a feasible subscale experiment whose results were reported in [82].

3.4.2 Scale Effects

Since there is no universal scaling methodology for aeroelastic problems it is impossible to discuss the particular effects that partial similarity would have on the experiment results. In general, the scale effects related to unfulfilled aerodynamic similarity, discussed in Section 3.2, are still relevant here. In fact, dissimilarity in Reynolds number could be a major concern for the study of aeroelastic phenomena in which partially separated flow is involved [6].

Furthermore, the problem of divergence between Mach number similarity and Froude number similarity, discussed in Section 3.3 and illustrated in Figures 3.6 and 3.7, acquires a more troubling dimension in aeroelastic scaling: when flow compressibility is a significant factor and Mach scaling is followed, the consequent dissimilarity in Froude number causes the model to fly at a different AOA than what the full-scale aircraft would. Due to the dissimilar attitude, the aeroelastic deformations are no longer equivalent to those of the full-scale aircraft [6]. Nevertheless, these effects are negligible for some aeroelastic problems such as the study of BFF mentioned above: in this case, the coupling between the short-period mode and the structural dynamics is much less sensitive to Froude number than to other factors like structural stiffness and the structural frequency [71].

3.4.3 Practical Limitations

Aeroelastic scaling, in general, combines most of the practical issues related to the aerodynamic and dynamic scaling methods. On the one hand, the similarity of aerodynamic forces and moments brings back the issues no. 2, 3, 4, and 6 from Table 3.2. The first of these, i.e. the difficulty to achieve similarity in Reynolds number illustrated in Figure 3.3, might be of special importance for some aeroelastic interactions in which detached flow plays a significant role.

On the other hand, the similarity of inertial forces and motions adds the issues no. 2, 3, 4, 5, and 6 from Table 3.3. Regarding the issue no. 2, and as mentioned before, scarifying Froude number similarity for Mach number similarity in compressible-flow conditions will generally cause inconsistent aeroelastic deformations due to mismatched AOA; although this effect might be less significant for certain applications. As for the issue no. 4, preserving the similarity in mass and inertial characteristics with different fuel systems on the full- and subscale vehicles becomes even more challenging in aeroelastic scaling since the mass distribution is also required to be similar.

Besides the issues accumulated from the previous scaling methods, aeroelastic scaling also presents some particular practical problems. Perhaps one of the most notable is the general difficulty of designing a subscale experiment in such a way that the aeroelastic phenomenon of interest is excited within the feasible flight envelope of the model. According to the similarity parameters in Equation (3.4), most of the models within the feasible region of Figure 3.8 would present a structural stiffness that is too high for experiencing observable aeroelastic interactions at the typical airspeeds achievable during SFT. The only exception would be the extremely flexible Human-Powered Aircraft (HPA) or case (d). A usual solution to this problem is to reduce the structural stiffness of the model and hence to sacrifice complete similarity with the full-scale vehicle. For instance, this was the solution adopted in the *X-56A* MUTT programme: the structural stiffness of the model was reduced to a level at which BFF could be experienced at lower airspeeds [78]. Another option is to design the whole subscale experiment starting from the available flight testing conditions and defining a hypothetical vehicle that would fit such conditions. This alternative was chosen in the FLEXOP project: the design of the test article was strictly bound to the mission design [84] and it did not correspond to any particular full-scale aircraft. Nevertheless, strong accelerations and decelerations were still required to reach the desired flight conditions during the short legs of the remote flight test. These manoeuvres demanded a high performance from the propulsion and braking systems, which were specifically optimised for this task instead of being scaled from full-scale characteristics [85].

Testing aeroelastic phenomena generates also special requirements on the data acquisition system: Most inertial instruments and data fusion algorithms used in flight dynamics incorporate various types of filters that are generally tuned for the detection of rigid body motion and therefore inhibit the typical frequencies at which structural dynamics develop. Measuring structural dynamics generally requires specific sensors and filters able to register considerably higher frequencies. The integration of other types of sensors on the airframe, such as strain gauges, may also be necessary [82].

All these practical issues are summarised in Table 3.4. It should be noted that these are based only on general characteristics and that certain aeroelastic problems may introduce significantly different concerns.

Table 3.4 *Summary of the main concerns and issues regarding aeroelastic scaling for subscale free-flight models tested in the open atmosphere.*

	Issue	Discussed in
1	Similarity of aerodynamic forces and moments introduces issues no. 2, 3, 4, and 6 from Table 3.2.	Section 3.2
2	Similarity of inertial forces introduces issues no. 2, 3, 4, 5, and 6 from Table 3.3.	Section 3.3
3	In addition to inertial characteristics, similarity in mass distribution is also required. This might be difficult to satisfy when the fuel system is considerably different.	[6, 78]
4	Dissimilarity in Froude number may cause inconsistent aeroelastic deformations due to mismatched AOA.	[6]
5	The structural stiffness prescribed by the similarity parameters might be too high for the excitation of aeroelastic phenomena at typical model flight speeds. Either structural stiffness is lowered or flight speed increased.	[6, 71, 78, 84, 85]
6	Logging structural dynamics requires specific instruments and filters designed for sampling higher frequencies than those found in flight dynamics.	[82]

3.5 Demonstrative Scaling

The term *demonstrative scaling* or, in short, *demo scaling* is a term proposed here to encompass particular uses of SFT that do not correspond with the conventional use of scaling laws. Demonstrative scaling can be defined as a subscale experimental method in which the test article does not necessarily share physical similarity with a full-scale vehicle, but features a scaled form of certain technology or capability that is yet to be proven in a relevant environment.

Such a definition covers a wide variety of cases and applications, ranging from basic functionality demonstration in a near-laboratory environment to sophisticated validation tests in the expected operational environment. Moreover, the mentioned attributes are shared by most of the research vehicles commonly known as *demonstrators*, but they do not correspond with near-production prototypes in which the features of interest are almost fully developed.

Technology demonstrators have always played, in one way or another, an important role in the progress of the aerospace industry. For example, a glance at the historical evolution of American experimental aircraft, including the well-known *X-vehicles* [15, 86] as well as other projects like the Rockwell *Hi-MAT* [14], reveals the critical effect that flight demonstration has on technology maturation. In the recent words of Eremenko [51]:

“The goal of flight demonstrators is to provide a rapid maturation pull as well as a definitive measure of technology maturity far more convincing than the TRL.¹ And this is for those technologies that pose a particular integration or industrialisation risk, or where the effects of the flight environment cannot be adequately simulated on the ground.”

A review of the historical progress of technology demonstrators also exposes an interesting trend: there seems to be a general tendency towards reducing the physical size of the experimental vehicles in most of the cases where the nature of the technology and its integration allow it. Furthermore, unmanned demonstrators are preferred in many cases. This is not totally unexpected considering that aircraft weight generally correlates well with complexity and cost, as Figure 3.11 shows.

But more interestingly, this trend also indicates how recent disruptive innovations in the fields of electronics, computer science, manufacturing, power storage, and communications have significantly altered the cost and capabilities of small, flying vehicles such as subscale models. Fairly sophisticated, unmanned test articles can now be built in much shorter time and with considerably fewer resources; factors that also enable their use for experimentation with more immature technologies.

¹The Technology Readiness Level (TRL) is a well-known figure of merit for measuring and describing the maturity of technology. First proposed by NASA in the 1960's, it currently consists of nine different levels whose descriptions can be found in publications such as [87].

Figure 3.11 Historical cost trend for a selection of American technology-demonstration vehicles, adapted from Beranek et al. [78].

Recent examples of demonstrative scaling

A clear example of demonstrative scaling in this context can be found in the increasingly large number of small companies and institutions that are currently testing radical Vertical Take-Off and Landing (VTOL) and electric aircraft concepts for urban mobility using relatively simple subscale models. Although it is difficult to quantify this phenomenon due to the lack of scientific publications covering these tests, an informed reader might have already noticed that the number of this kind of projects has exploded in during the last decade. Some of these are analysed in [88].

Established institutions like NASA are also increasingly relying on low-cost subscale platforms for the experimentation with technologies at low TRL. An example is the *GL-10 Greased Lightning*, a tilt-wing subscale model with distributed electric propulsion. This low-cost platform has been used to experiment with distributed propulsion for acrchortvtol as well as to investigate flight control and transition strategies [89, 90]. Another recent example is the *Prototype-Technology Evaluation and Research Aircraft* (PTERA). This research vehicle, developed for NASA by a small Unmanned Aerial Vehicle (UAV) manufacturer called Area-I, resembles a typical single-aisle transport at about 10% scale and it is designed to be modular and easily reconfigurable. In a few years, this platform has already been

used to evaluate technologies as diverse as flow-circulation control for Short Take-Off and Landing (STOL) [91], and morphing wings with folding wingtips [92].

A similar modular design was adopted in the European *Innovative Evaluation Platform* (IEP), also known as *Fexi-Bird* [21, 22, 93]. The geometry of this modular vehicle was also representative of a modern transport design with slight variations in its configuration. It was intended to perform low-cost flight tests for investigating noise and environmental issues, flight dynamics, and techniques for recovery from hazardous flight conditions.

Aurora Flight Sciences used a 20% scale aircraft, called *VTOL X-Plane*, to demonstrate the feasibility of the future *XV-24A LightningStrike* VTOL vehicle with tilt-wing and hybrid-electric distributed propulsion [94].

In the BAE Systems research programme *FLAVIIR*, a light platform with a rather unconventional configuration was used to demonstrate fluidic thrust vectoring, circulation control devices, and advanced flight control laws [18, 95]. Moreover, there are multiple examples of the use of similar subscale models as a low-cost test-bed for advanced flight control techniques, such as references [19, 75, 77, 96, 97, 98, 99]. In other cases, they have been used for evaluating novel system identification techniques and flight-test manoeuvres [100]; or even the atmospheric influence on the flight performance of micro air vehicles [101].

In [25, 102, 103], subscale models are used to evaluate the characteristics of various unconventional configurations. Furthermore, besides NASA's experiments with the PTERA, research on unconventional and morphing structures has also been carried out in [104, 105, 106, 107].

Additionally, in [108, 109, 110], simple platforms were used to test and demonstrate the feasibility of flow and vehicle control by means of plasma actuators; a milestone that already entails a direct increase of the TRL.

In [32, 33], the vehicles demonstrated the maturity of flight guidance and automation technologies for Unmanned Aircraft System (UAS); while in [111, 112] small models were used to test various kinds of enabling vehicle technologies for future UAS traffic management systems.

Yanagihara et al. [13] demonstrated and validated autonomous flight technologies for future space transportation systems based on fixed-wing reentry vehicles.

Furthermore, Jung et al. proposed in [113] a methodology for conducting scaled sonic-boom flight tests using subscale models.

As a matter of fact, three of the experimental platforms mentioned in the aeroelastic scaling section (3.4) could also be included in this section: the *X-56A MUTT* [78, 79, 80], the *FLEXOP* demonstrator [83, 84], and the modified COTS model by Ouellette et al. [82] leave aside the complete similarity with a full-scale vehicle in order to provide better capabilities for experimentation and demonstration within a feasible model flight envelope.

Impact of demonstrative scaling

The main strength of subscale technology demonstrators is the reduction of complexity, risk, and therefore cost over traditional research vehicles developed at full-scale. These characteristics, added to shorter development and iteration times, make them suitable for early experimentation with immature technologies in a context of relatively low funding.

Low-cost demonstrators could be already useful for applied research at TRLs as low as two and three, although their most valuable capability is perhaps that they can be used for pushing the TRL across the first part of the technology development phase, between TRL 4 and 6 approximately. This challenging phase, familiarly known as *The Valley of Death* [114], is usually characterised by a lack of sufficient resources to face the growing risk and cost as well as the remaining uncertainties. Figure 3.12 tries to illustrate this situation and how low-cost subscale demonstrators could help to bridge the gap between the initial and final part of the technology development phase.

Figure 3.12 Phases and factors involved the development of a new technology or system according to the TRL scale [87]; and adapted from [115]. Low-cost subscale demonstrators could help bridging the central gap, familiarly known as *The Valley of Death* [114].

Nevertheless, a question might arise from the lower levels of technology maturity: is it always convenient to place valuable resources in scaled flight demonstration? It is generally agreed that designing and performing practical experiments is a resource-consuming endeavour, and it has also been argued that virtual experiments often require fewer resources and are easier to reproduce and store [45]. It seems evident that there cannot be a categorical answer to this question. Different scenarios and technologies might require different or combined approaches. However, it may be interesting to also consider in this debate other by-products of experimental flight demonstration that are not exclusively of technical nature: its positive effects on confidence and motivation.

An important side-effect of building flight demonstrators is the motivating effect that it has on engineers and technologists, especially in the current scenario where large aerospace programmes are few and far between. Eremenko [51] acknowledged recently this effect on a large organisation like *Airbus*, and also added another aspect: “*[Flying demonstrators] is a tool for attracting top talent, and an essential one for us [large and established companies] to compete with the start-ups, the Googles, and the Amazons of the world*”.

Kress [3] highlighted similar motivational effects after an experimental campaign at *Grumman*, in which multiple R/C models were used to investigate and demonstrate conceptual V/STOL aircraft. This author also mentioned the proficiency of these models to reveal unforeseen design problems that were not detected previously.

Positive effects of flight demonstration have also been reported in academic environments [34], where the authors found in subscale models a motivating tool to transfer practical experience and confidence in solving applied engineering problems.

4

Flight Test Instrumentation

Measuring equipment is essential to obtain quantitative results from flight testing. The response of the aircraft must be registered and analysed in order to identify and quantify the factors that cause it. But obtaining an accurate record of the real motion of an aircraft in the air is by no means easy. Since direct measurements are often impossible, data gathered from different indirect sources must be reduced and combined to estimate the state of the aircraft.

The block diagram shown in Figure 4.1 represents a typical process of modelling the flight characteristics of an aircraft from flight test data using a system identification approach. This chapter focuses mainly on the measurement of the aircraft response to test manoeuvres; a part which is highlighted in grey on this figure.

One of the typical challenges in designing Subscale Flight Testing (SFT) experiments is the lack of suitable data acquisition systems. Flight-certified or aviation-grade hardware is generally too heavy, too large, and too costly for small subscale aircraft. Its purchase cannot be motivated since the obtained data is rarely intended to be used in high-fidelity flight simulators. On the other side of the spectrum, manufacturers such as Eagle Tree Systems [117] commercialise inexpensive logging equipment for the aeromodelling hobby market; however, the performance of these systems is often insufficient for research purposes.

A notable attempt to develop an appropriate data acquisition system was made at Linköping University in 2008 using a Diamond Systems PC board *Athena* with a Pentium-III-class processor running a streamlined Linux kernel as operating system [37]. Unfortunately, this system became slightly oversized for some of the platforms and it was affected by timing problems caused by the non-real-time operating system. The following attempt focused on minimising the hardware in order to reduce cost, size and power consumption. The new

Figure 4.1 Typical process of modelling an aircraft from real flight data using system identification, adapted from Hamel et al. [116]. This chapter focuses on the part corresponding to the measurements, highlighted in grey.

system, based on a 32-bit *Atmel* microcontroller, reached a fairly mature state by 2010, as described by Staack et al. in [39]. Since all the firmware in this system was programmed from scratch, its development was labour-intensive and its performance was limited in some aspects such as in the number of Input/Output (I/O) channels.

The improvement of the price-performance ratio of miniaturised electronics during the last decade has been tremendous. This improvement, together with a desire of exploring the possibilities of control augmentation, motivated the design of a new flight control and data acquisition system between 2015 and 2016. The development of this new system has been an important part of the work done this thesis. This chapter presents the results obtained with respect to the current version, completed in 2017.

4.1 General System Characteristics

The new data acquisition system was intended to enable SFT of low-cost subscale models with the ultimate purpose of identifying their flight characteristics. Consequently, this system had to be appropriate for measuring the dynamic motion of small platforms. There was also a strong interest in evaluating the capabilities of a *low-cost* system. As a proof-of-concept on its own, the resources allocated to the development this system were constrained to the minimum: it had to be inexpensive and require no more than a person to be developed and maintained. In this context, a *low-cost* data acquisition system can be roughly defined as a system in which all its hardware and software is estimated to have a value below 1000 Euro or 10000 SEK; not including the essential components of the main R/C link.

The main high-level requirements that such a system needed to fulfil could be summarised as follows:

1. Use low-cost sensors and processors.
2. Use COTS components where possible.
3. Preferably use open-source hardware and software.
4. Modular structure, high flexibility for reconfiguration.
5. Lowest weight possible, in all cases below 500 g.
6. Smallest size possible and practical form factor.
7. Sample rate of at least 50 Hz for main state variables.
8. Low power consumption and low operating voltage.
9. Scalability and ease of development.
10. Possibility of further development as a Flight Control System (FCS).

The preference of low-cost components (1) was not only motivated by economic resources, but also by the aim of investigating the performance of the new low-cost sensors and processors that have been disrupting the market during the last decade along with the introduction of smart-phones and other portable devices; see Figure 2.4. Indeed, recent studies such as [118] indicate a surprisingly satisfactory performance of low-cost Micro-Electro-Mechanical System (MEMS) sensors used for data acquisition in small Remotely Piloted Aircraft (RPA), considering that their cost is several orders of magnitude lower than traditional, aviation-grade inertial sensors.

The requirements regarding low weight, small size, and modular structure (4,5,6) originated mainly from the intention of using this system, or derivatives of it, in a wide variety of subscale platforms, ranging from jet-powered aircraft

with a Take-Off Mass (TOM) of 20 kg to small electric models under 1 kg of TOM.

The preference of a flexible system, using open-source software and hardware (3,9), responds to the aim of further developing, modifying, and expanding easily such a system according to future changes in requirements or applications.

The possibility of developing a system that, while acquiring data, could function as a closed-loop FCS (10) was also initially considered. Its study, initial configuration, and different trials carried out with small aircraft are described in Paper [1], and represent an important part of the development work. Nevertheless, it was decided later to pause this development and to prioritise the data-acquisition capabilities as a passive system; a decision mainly motivated by the additional risk involved in flight testing larger aircraft and the excessive development time for meeting the corresponding reliability goals.

4.1.1 Base System

Fortunately, the requirements specified before agree well with the new generation of hobbyist and semi-professional autopilot systems that have emerged along with the recent boom in the commercial drone industry. The first process of an autopilot system is to sense and evaluate the current flight status of the aircraft by using a variety of sensors; an information that enables the primary stability control loop as well as further navigation control loops. Such a capability makes an autopilot system a potentially good data acquisition system.

A general survey of suitable autopilot systems, focusing on open-source hardware, was carried out at the beginning of the development process, in 2014. Although a fully satisfactory solution was not found, two potential candidates were identified: *Paparazzi* autopilot project [119] and *PX4/Pixhawk* autopilot project [120]. A similar survey including commercial and custom-built hardware options was carried out later by Dantsker et al. [121]. While these authors decided ultimately to develop a new data acquisition system from scratch, it was preferred here to select an existing autopilot system as a base and to develop it further to fit all requirements. The selected base system was a *Pixhawk* flight controller hardware [120] together with the *ArduPilot* open-source software in the version *Plane* [122].

4.2 System Architecture

The base system, a *Pixhawk* flight controller set, was expanded both with software modifications and new hardware devices in order to improve the logging performance and to include the measurement of additional states. Figure 4.2 shows a diagram of the current version of the data acquisition system, as integrated on the GFF demonstrator. The system consists of multiple distributed devices instead of a centralised unit. This facilitates not only its integration,

but also to optimise the location of each component according to physical, functional, or electromagnetic conditions. Some of the main components are briefly described below.

Figure 4.2 Layout of the main devices and sensors that compose the current version of the data acquisition system installed in the GFF platform.

Main Processing Board with Integrated Data Logger

The main processing board consists of a COTS Pixhawk core unit. Detailed characteristics of this device can be consulted in reference [120]. A main 32-bit processor, and additional safety processor, two Analog-to-Digital Converter (ADC), several sensors, and a data logger with a Micro-SD memory card port are built into the main Printed Circuit Board (PCB). The built-in sensors include:

- a barometric pressure sensor Measurement Specialities *MS5611*;
- an Inertial Measurement Unit (IMU) composed by a STMicroelectronics *LSM303D* three-axis MEMS accelerometer and magnetometer, along with a STMicroelectronics *L3GD20* three-axis MEMS digital gyroscope;
- and a second IMU composed by a InvenSense *MPU-6000* six-axis MEMS motion tracking device.

These consumer-type MEMS sensors are inexpensive and are not certified for flight operations or technical measurements. Different types of noise can compromise severely the attitude estimation. Nevertheless, even in the harsh environment found in small R/C aircraft, this type of sensors combined with appropriate filtering algorithms can offer a satisfactory performance during short periods of time [118, 121]. In the software used here, ArduPilot version Plane [122], approximate state estimations are obtained by filtering sensor data using an Extended Kalman filter (EKF). This is an algorithm that linearises the system equations around the best state estimate available before applying the standard Kalman filter equations; see [123] for more information. One instance of this computation is run independently for each IMU, ensuring not only redundancy but a more reliable estimation.

Only minor physical modifications have been performed on the Pixhawk main processing board: one of the units has been modified with a tube that would allow the built-in barometric pressure sensor to take measurements via an external static pressure port, instead of measuring the ambient pressure inside the fuselage. This modification aims at reducing the noise in the pressure measurements caused by the internal jet turbine engine in some of the subscale aircraft; however, it has not been flight tested at the time of writing.

GNSS receivers and additional magnetometers

The system includes two different COTS non-augmented Global Navigation Satellite Systems (GNSS) receivers which also incorporate three-axis digital magnetometers built into their PCB. Electromagnetic noise caused by onboard equipment can disturb sensible sensors and receiver antennas, as measured by Dantsker et al. [124]. Since both GNSS antennas and magnetometers are highly sensitive to electromagnetic noise [118, 121], they are often grouped into the same module in order to be installed in a part of the airframe far from the main noise sources.

One of the receivers comprises a U-blox *M8N* module able to connect simultaneously with up to three of the main GNSS (GPS, Galileo, GLONASS, BeiDou); as well as two digital magnetometers: Honeywell *HMC5983*, and STMicroelectronics *LIS3MDL*. The other receiver comprises a U-blox GPS module *NEO7* and a single digital magnetometer Honeywell *HMC5883L*.

Both GNSS receivers usually operate at the same time. The ArduPilot software evaluates the accuracy of each one and selects or blends them as needed. Although not used here, GNSS augmentation would be an effective solution to improve the accuracy of the position estimations.

Air-data boom

Flow conditions such as angles of incidence, dynamic and static pressures are measured directly by using air-data booms designed and built in-house. These

booms normally integrate a pitot-static probe and two flow-angle transducers, one for AOA and another for Angle-Of-Sideslip (AOS).

These flow-angle transducers consist of mass-balanced vanes rotating on ball-bearings. The relative angles are measured using magnetic-induction rotary encoders extracted from inexpensive hobbyist-type R/C servos *HK28013DMG*. These encoders have a linear analogue output that is read via two of the available ADC ports on the main Pixhawk processing board. Posterior corrections are done in the software and include not only calibration curves but also account for the dynamic effects of the rigid-body movement of these vanes around the CG of the aircraft.

Figure 4.3 shows the air-data boom currently installed on the GFF, manufactured in carbon fibre with moving parts milled in aluminium. More information is available in [40]. Simplified, lighter versions of this boom design, featuring only an AOA transducer, have also been built for small subscale platforms weighing less than 0.9 kg of TOM; see Figure 4.4. In this case, the carbon fibre boom was completed with parts 3D-printed in plastic [V].

Figure 4.3 Air-data nose-boom with two flow-angle transducers installed on the GFF platform.

Control-surface position sensors

The original sensor-support capability of the Pixhawk hardware was extended by the addition of an Adafruit 16-Bit ADC converter *ADS1115*, which communicates with the main processing board via *I2C* protocol. This enabled four additional analogue inputs that were used for the integration of four control

Figure 4.4 CAD model of a small air-data boom comprising a pitot-static tube and a single flow-angle transducer. The sensor housing, the vane arm, and the vane were 3D-printed in plastic.

surface position sensors on the GFF platform: one for each canard surface and one for each elevon, see Figure 4.2.

The real position of the control surfaces was previously estimated from the output signals sent to the servo-actuators and corrected with a calibrated model of the actuation mechanisms, as explained in paper [II]. Nevertheless, measuring directly the real position of the actuators reduces the uncertainty and simplifies the analysis of the flight data.

Voltage and current sensor

Power sensors typically measure the main and radio battery levels in hobbyist rigs. Here this set-up is only used in the smaller electric-powered test-bed aircraft. On the jet-powered platforms, it is used to monitor the fuel pump performance in order to estimate the fuel consumption.

Video camera and OSD

Light micro-cameras, with or without *On-Screen-Display* (OSD) of real-time flight data, are used to capture phenomena of interest such as the performance of the flow-angle transducers or the attitude of the aircraft in reference to the horizon. These external cameras are installed or removed depending on the experiment.

Main control link

The R/C system used to operate the aircraft is generally not included in this data acquisition system, although its built-in telemetry system is used by the pilot to monitor critical flight-safety parameters such as the strength of the radio link or the voltage of the systems onboard. The R/C system used in most of these tests is a JetiModel *DC-24* [125] and operates in the 2.4 GHz band. The aircraft is equipped with a main dual-antenna receiver and a backup receiver working on the 900 MHz band.

Telemetry and ground station

The data acquisition system uses a separate COTS, low-cost, open-source telemetry system working on the 433 MHz band. This link is bidirectional and totally configurable. The unit on the ground is typically an ordinary laptop running the open-source software Mission Planner [126]. The limited bandwidth constraints the number the number of parameters and the sample rate that can be transmitted in real time to the ground station. Therefore, this link is mainly used to monitor the reading of certain sensors and the general health of the data acquisition system.

4.3 Calibration

Different calibration techniques were used depending on the type of sensor and the platform in which it was installed. A detailed discussion of these procedures is not intended here, and only some particular observations will be mentioned.

In general, the calibration of the inertial instruments is effectively managed by the ArduPilot software. After some initial calibration of manufacturing and installation offsets, the software is able to recalibrate these sensors upon activation by using the gravity vector and data from other instruments. This process takes usually less than 60 seconds, and it is usually performed before every flight once the electronics have reached nominal working temperatures.

Similarly, the calibration of the digital magnetometers is performed by the autopilot software before and even during the flight if new perturbations are detected. The EKF algorithm is also responsible for this process.

An accurate calibration of angle transducers such as control-surface position sensors and flow vanes was done following basic geometrical principles in the laboratory. Laser beams were used to increase the measuring distance and hence the precision.

The calibration of the airspeed transducer, the pitot-static probe, can be more challenging. For small and low-cost platforms it is usually sufficient with a manual calibration based on flight data obtained by flying circular patterns at a constant altitude, see Figure 4.5. Averaging the ground speed provided by the GNSS during circular flight cancels the effect of the wind and offers a

good estimate of the real airspeed. The ArduPilot software has also a dedicated algorithm that can perform a similar in-flight calibration based on the estimations of the EKF.

Figure 4.5 Example of a manual calibration of the airspeed transducer using flight data from circular patterns. This approach can be useful for small subscale models flying at low AOA.

Nevertheless, the large air-data boom installed on the GFF was also calibrated for airspeed and AOA variations at the wind tunnel of the Instituto Tecnológico de Aeronáutica (ITA) in Brazil. Figure 4.6 shows some of the data obtained in this experiment. A mathematical model for the airspeed-transducer behaviour was generated and implemented in the flight data analysis software.

Another interesting factor related to the calibration of some sensors is to obtain the right model for the dynamic rotation of the aircraft. High angular rates can introduce errors in the measurements of some sensors, such as accelerometers and flow-angle vanes. Assuming that the centre of rotation is the CG and that the aircraft is rigid, these dynamics can be mathematically formulated and accounted for. The main challenge usually lies in measuring the CG of the aircraft in three dimensions. A specific experiment was designed to determine its location with sufficient accuracy: the aircraft was hanged from a fixed structure so its CG could naturally align with the central vertical plane by the effect of gravity. A vertical laser beam was then used to identify and mark the section of the fuselage crossed by this vertical plane, as shown in Figure 4.7. By repeating the same operation at different hanging angles, it was possible to obtain different planes crossing the CG from different directions. These measurements were later transferred to a CAD model to compute the exact location of the CG. The entire experiment was repeated for different configurations, such as with the landing gear extended and retracted.

Figure 4.6 Calibration of the airspeed transducer of the large air-data boom, performed at the wind tunnel of the Instituto Tecnológico de Aeronáutica (ITA) in Brazil. This figure shows the relative error of the pitot probe at different AOA and for various wind-tunnel airspeeds.

Figure 4.7 Technique used for determining experimentally the position of the CG in three dimensions. The aircraft is hanging freely at different angles while a laser beam shows the vertical plane that crosses the CG.

4.4 Logging Rates

The open-source autopilot software *ArduPilot* [122] was also modified in order to improve its sensor sampling and data logging capabilities at the expense of losing autopilot and auto-navigation performance; functions which are currently not used in the larger research platforms at Linköping University. The software modifications included the integration of the external ADC and its channels, as well as an increase of the sampling and logging rates for those sensors and parameters that are of most interest for flight dynamics.

The following Table 4.1 presents a summary of the principal parameters of interest for flight dynamics, along with the respective number of instances and logging rate available with the current version of the data acquisition system. Observe that some of these parameters are derived quantities and do not correspond directly to raw sensor measurements.

Table 4.1 Summary of the main parameters logged by the current version of the data acquisition system, indicating the number of instances (parallel measurements), and respective logging rates.

Parameter	Number of instances	Logging rate [Hz]
Attitude relative to the ground	2	100
Heading	2	100
Angular rates	2	100
Accelerations	2	100
AOA, AOS	1	100
Pilot inputs	1	100
Output signals to actuators	1	100
Control surface positions	1	100
Airspeed	1	25
Barometric altitude	2	25
Air temperature	2	25
Voltage, current	1	25
GNSS position and altitude	2	5
System health, error flags	1	2

5

Flight Test Methods

The goal of flight tests is generally to acquire empirical data that can be used to develop and validate mathematical models, performance figures, or capabilities that were initially estimated during the design phase. Flight testing full-scale manned aircraft is, in general, an expensive activity in terms of both time and money. It is no surprise that manufacturers strive to decrease the time spent in flight testing during development and certification. An important part of the current research in this field is therefore aimed at increasing the efficiency of the entire data acquisition, reduction, modelling cycle. Publications such as Morelli [127, 100] and Larsson et al. [128] are some examples of the efforts to improve the flight test techniques and the parameter estimation process.

The block diagram in Figure 5.1 presents again a typical outline of the entire process of modelling an aircraft from real flight data using system identification. This chapter focuses on the very first part of the process, highlighted in grey.

Subscale Flight Testing (SFT) shares most of these characteristics but it also presents some particular challenges. Despite eliminating the added risk and infrastructure associated with manned aircraft, operating and testing Remotely Piloted Aircraft (RPA) in a safe and efficient manner is still a challenge for organizations with limited resources such as universities and small companies. This factor may be one of the main barriers preventing a more generalised use of SFT in research, education, and industrial applications. This chapter describes the work done towards finding a testing methodology that, while complying with the current regulatory framework, could improve the data quality for performance evaluation and system identification of fixed-wing RPA at a minimum economic cost. The topics discussed here are closely related to those included in paper [III].

Figure 5.1 Typical process of modelling an aircraft from real flight data using system identification, adapted from Hamel et al. [116]. This chapter focuses on the part corresponding to the aircraft flight and system excitation, highlighted in grey.

5.1 Operation of RPA: Types and Regulations

The simplest way of operating a subscale, unmanned aircraft is to operate it in real time from the ground using a Radio Control (R/C) system or a similar control station. The entire system is then commonly referred to as Remotely Piloted Aircraft System (RPAS). Generally, the ability to perform autonomous flight or autonomous navigation does not present any relevant advantages for SFT activities. On the contrary, such a feature would increase complexity, risk, and development cost. RPAS are often included in the broader category of Unmanned Aircraft System (UAS) with regard to civil air regulations. Figure 5.2 tries to graphically explain this classification.

In most countries, the current regulatory frameworks for the operation of civil

Figure 5.2 Typical classification of aerial vehicles according to how they are controlled.

UAS create a notable step between certified operations within Visual Line-Of-Sight (VLOS) and Beyond Visual Line-Of-Sight (BVLOS) in terms of cost and requirements [129]. This issue is not caused by the cost of the extra technical equipment needed for Extended Visual Line-Of-Sight (EVLOS) and BVLOS operations: inexpensive systems are already available in the market and they are sometimes used for hobby activities. Instead, the extra cost and complexity are caused by the difficulties and uncertainties derived from introducing this kind of unmanned vehicles in conventional controlled airspaces. A civil operator willing to obtain such permission is usually forced to either certify the system according to nearly-full-scale standards or to operate inside costly segregated airspaces [130, 131, 132, 133]. Therefore, the natural choice for civil operators of low-cost subscale models is to fly in conventional airspace following VLOS rules.

Figure 5.3 exemplifies this situation by comparing various cost estimates for flight testing a civil RPA similar to those used for research at Linköping University; see Table 3.1. These cost estimates are not only direct operating costs but a sum of factors such as the estimated cost of qualified personnel, transportation, renting of appropriate facilities, cost of extra equipment for each type of operation, and predicted cost of certification or approval procedures. These costs were estimated based on the current Swedish civil air regulations [133], previous experience in similar operations, experts' opinions, and current commercial prices as of year 2018. From the two different scenarios presented, nearly all the flight test campaigns carried out by Linköping University are similar to the one labelled as "Campaign 1".

Figure 5.3 Comparative of various cost estimates for flight testing a subscale research platform similar to those flown by Linköping University in Sweden, year 2018.

For operations within VLOS, the maximum allowed distance between the aircraft and the operator is determined by the specific definition in the local regulations; however, the most common presumption is 500 meters. The maximum allowed flight altitude is usually between 120 and 150 meters Above Ground Level (AGL), although this is subject to local airspace rules or temporary clearances from the air traffic control services. The result is a cylindrical airspace of very limited dimensions, often affected by ground turbulence and obstacles on the surface. While flight testing BVLOS would be more convenient, the substantial step in cost and complexity motivates the choice of flight testing within VLOS, at least for low-cost subscale aircraft.

5.2 Specific Methods for Flight Testing within VLOS

Flight testing methods have been extensively discussed in the literature. Publications [134] and [135] are two typical references that focus entirely on manned aircraft. In addition, other publications dealing with flight testing RPA have begun to appear [16, 136, 137, 138, 139]. Although flying RPA under VLOS rules has become a relatively common practice, it is still rare to find published discussions about this particular scenario. Stahl et al. [84] and Sendner et al. [85], both involved in the FLEXOP project (see Section 3.4), seem to be the

only recent publications related to this issue.

Flight testing RPAS in general, and under VLOS rules in particular, requires different approaches than those traditionally followed in manned aircraft. The short testing time, the need for constant manoeuvring and the imprecision of remotely executed excitation manoeuvres are some of the factors that complicate this task. These challenges become even more evident when the test objects are heavy and complex aircraft models, such as dynamically scaled vehicles often used in research projects (see Section 3.3).

Figure 5.4 illustrates the reduced time available for manoeuvring inside a 500-meter test-window; the typical usable length of a straight trajectory in flight within VLOS. Experience has shown that test windows larger than 500 meters are difficult to achieve due to the need for appropriate safety margins, aircraft manoeuvrability, and visibility constraints. This figure represents an optimistic estimation based on straight-and-level flight along the entire test window. In the real world, dynamic flying and weather conditions may significantly alter the available time to execute each test manoeuvre.

Figure 5.4 Estimation of time available inside a 500-meter test window for different subscale aircraft, assuming straight-and-level flight. These models correspond to the cases (a), (b), and (c) from Table 3.1.

5.2.1 Infrastructure

The main advantage of flight testing RPA within VLOS is that it often does not demand a complex infrastructure. The resources needed to support, operate

and maintain these systems are in most cases only slightly more than those required by large R/C models operated by hobbyist for leisure activities.

It is difficult to make general statements about the location of appropriate test facilities: requirements such as runway, airspace, remoteness, and supporting equipment are usually based on the test article, the specific research plan, and the pertinent internal or external regulations. Other programmatic factors such as transportation cost and expenses may also play an important role [19]. The main advantage of operations within VLOS is that tests are not restricted to general-aviation airfields, but can also be carried out in model-flying fields, a convenient option that increases the number of available locations and lowers the operating cost.

For operation in civil airspace, the minimum crew and the competences required may be directly specified by the competent aviation authorities in the UAS regulations. For platforms with a Take-Off Mass (TOM) lower than 25 kg, as most of the research platforms flown by Linköping University, the current Swedish regulation specifies requirements only for the Pilot In Command (PIC), who must behold an approved certificate of competence [133]. However, for platforms with a TOM higher than 25 kg, up to four different roles are specified in this regulation: accountable manager of operations, flight director, technical manager and PIC.

Besides these requirements, the roles needed for conducting remote flight testing in an efficient manner may differ from those formally required. Based on the experience gathered during the flight-test campaigns carried out at Linköping University with platforms up to 20 kg of TOM, three different roles have been identified as the minimum crew needed on the field in order to achieve satisfactory and safe flight tests within VLOS:

- test conductor, responsible for controlling the test execution, systems' health, and data acquisition;
- pilot (PIC), flying the aircraft remotely from the ground control;
- test monitor, supervising the safety area and evaluating the data quality between flights.

This configuration should be seen as a functional minimum, applicable to platforms, systems, and testing facilities similar to those used at Linköping University. Moreover, the availability of additional resources or particular requirements can lead to a more numerous crew; case in which other additional tasks, such as graphical documentation of the tests, can be also made easier.

5.2.2 Concept of Operations

As mentioned before, the maximum distance between the PIC and the aircraft in VLOS operations is commonly assumed to be 500 meters. The combination of this limit with a maximum altitude of approximately 120 meters AGL results

in a cylindrical airspace of very limited dimensions. The methodology proposed here divides this space into three areas:

- a safety area, where only crew members are allowed;
- a nominal manoeuvring area;
- and a designated test window.

Figure 5.5 shows an example of this distribution during a typical flight test carried out with the GFF platform. In general, the orientation and placement of the different areas may depend on ground obstacles, visibility, sun position, and wind direction.

Figure 5.5 Trajectory during a flight test of the GFF platform, following the proposed concept of operations.

The research requirements are transformed into a flight test plan by breaking down the desired scenarios into short manoeuvres or *test points*. As in manned-aircraft, both flight time and risk can be minimised by carefully choosing the sequence of test points [135]. In this scenario, it is recommended to also pay attention to local atmospheric conditions, available airspace for manoeuvring, and fuel-weight fluctuations; where the latter could notably affect light-weight platforms. It has been observed that, given the short duration of the flights and the exposure to arbitrary external perturbations, it may be convenient to leave room in the test plan for eventual repetitions of test points or even entire sequences. Several flights per session are normally possible and keeping a certain degree of flexibility - although avoiding improvisation - can be beneficial.

The proposed concept of operations is outlined in Figure 5.6. The three roles presented earlier should be in constant communication and their tasks should not be exchanged during the entire flight, which for the platforms used in the experiments typically lasts between 10 to 20 minutes. The PIC should not lose direct visual contact with the aircraft at any time between engine start and shut-down, and therefore relies on spoken communication and audio signals to gain complete awareness of the aircraft status and the surroundings. Standardised flight-test cards streamline the communication between the pilot and the test conductor. During the flight, the test conductor reads out the respective test point to the pilot including the desired airspeed, attitude and aircraft configuration at the beginning of the manoeuvre. In addition, the test conductor can write down on the test card any relevant observation that needs to be documented. Furthermore, the pilot workload may be reduced further if the excitation manoeuvres are pre-programmed, a technique that eliminates the need for memorising the execution of each test manoeuvre. Besides a partial real-time monitoring of the sensor signals, during all the experiments carried out, the acquired data was downloaded from the aircraft and verified immediately after each landing.

Figure 5.6 Diagram of the proposed concept of operations for safe and efficient flight testing within VLOS.

In case of an emergency or loss of control, there must be a well-established and well-trained flight termination procedure to immediately bring down the aircraft within the designated safety area and with the minimum energy possible. The aircraft should have the necessary onboard system to carry out this procedure autonomously even if the control link is lost. In fact, this is sometimes a condition specified in civil UAS regulations, as in [133].

5.2.3 Automation of Manoeuvres

One of the main contributions regarding specialised testing methods is perhaps the development of a novel method for commanding pre-programmed excitation manoeuvres without the need for a closed-loop flight controller or an on-line ground station. On the one hand, this benefits the smallest low-cost platforms by further simplifying their development. On the other hand, it may allow more complex platforms to perform automated flight test manoeuvres even before their flight control system is mature enough to fly autonomously, or in the case that this is not allowed by the regulations. In any case, this method reduces effectively the workload of the pilot, who can focus on the challenging task of flying the aircraft through the narrow manoeuvring area at the required speed, altitude and attitude; see figures 5.5 and 5.6.

This method is based on a custom-made application written in *Lua* language [140] that runs on the radio-control transmitter in parallel to its standard software. The capability of interpreting *Lua* scripts was recently introduced by some R/C system manufacturers and it has been used mainly by hobbyists to visualize telemetry data in sophisticated ways or to customise user interfaces. This capability was used here to create a program able to actuate flight controls following complex pre-defined signals. The resulting *Lua* application makes it also possible to easily configure an entire sequence of test points. The application can use an external library of customised input signals that can be updated or extended at any moment. Both analytically-described functions and discrete point-defined signals can be loaded. Once a test sequence has been configured, the script can also be used as electronic documentation for each flight test. Figures 5.7 and 5.8 illustrate some of these features.

During flight, the operator selects the desired test point and triggers the manoeuvre by flipping and holding a switch. The corresponding signals are then executed on the intended control surfaces according to the specified timing and recurrence. An information window, displayed on the transmitter's screen, shows the test point status and any incidences, see Figure 5.9. In addition, audible signals, messages, and flight parameters are played out through the transmitter's speakers to inform the pilot without losing visual contact with the aircraft. Several safety mechanisms have been introduced during the development of the application in order to avoid that any malfunction could compromise the flight safety. Ultimately, the pilot can abort the process and regain manual control at any time by releasing the trigger switch. Due to the current hardware limitations, the signals can be transmitted up to a maximum frequency of 50 Hz. This rate is close to the typical refresh rate of radio-control systems and, so far, it has been sufficient for the intended applications, such as the study of the short-period modes of subscale models.

The functionalities of this flight test application are still being developed: The latest release makes use of *virtual flags* to mark the exposure periods on the logged data in order to allow automatic selection and post-processing of the desired flight segments.

Figure 5.7 Various types of input signals that can be generated with the flight test application.

Figure 5.8 Screenshots from the flight test application, here integrated into a transmitter Jeti Model DC-24: hardware setting menu (left), and configuration of test points (right).

Figure 5.9 Screenshots from the flight test application, here integrated into a transmitter Jeti Model DC-24: information window displayed to the operator during the execution of a test point.

5.2.4 Manoeuvres for Performance Evaluation

During performance flight testing, manned aircraft are usually flown very accurately in still air and the large airspace available allows conducting stable test points [134, 135, 141]. As discussed earlier, this is seldom possible when flight testing RPA within VLOS. The time to execute each test point is extremely limited (see Fig. 5.4) and steady trimmed flight is hardly achievable. The acquisition of performance data such as lift-to-drag polars using a traditional approach becomes therefore quite challenging. Short manoeuvres with a rich information content would be preferred over an extensive exploration of the flight envelope.

The advantages of using certain dynamic test techniques, i.e. involving dynamic manoeuvring instead of steady conditions, have been mentioned previously in the literature [141]. Although they are usually proposed for manned aircraft, dynamic test manoeuvres seem very well suited for performance testing of RPA under the constraints of VLOS. Furthermore, a literature review has revealed that the following manoeuvres summarised in Table 5.1 could facilitate the acquisition of performance data in such conditions.

Table 5.1 Various dynamic flight manoeuvres considered useful for aircraft performance evaluation within VLOS. Some of these have been inspired by manned-aircraft techniques described in [141].

Manoeuvre	Conditions	Results
Slow-down: deceleration to high AOA by pulling up	Constant thrust, any configuration, load factor close to 1g	Several trim and polar points up to maximum AOA
Vertical "roller-coaster": gentle push-over followed by pull-up	Constant thrust, any configuration, load factor from 0g to 2-3g	Several polar points around trim point, lift variations
"Bleed-off" closing banked turn in horizontal plane	Constant thrust, constant altitude, load factor increasing from 1g to maximum	Several polar points up to maximum load, load factor vs AOA
"Wind-up" closing spiral turn ¹	Constant thrust, constant speed, load factor increasing from 1g to maximum	Several polar points up to maximum load, load factor vs AOA

¹This manoeuvre could be infeasible when the flight is performed at low altitude over the terrain since it involves trading altitude for speed.

5.2.5 Manoeuvres for Flight-Mechanical Characteristics

A similar problem affects the evaluation of flight-mechanical characteristics: there is a very short time to excite the desired flight-mechanical motion. Hence, it is necessary to find test manoeuvres and input signals that maximise the amount of information with a minimum exposure time.

An approach that could be well-suited for these conditions is the utilisation of simultaneous, uncorrelated inputs such as multisine signals [100, 127]. This approach is based on the fact that two or more sine signals are uncorrelated if they have different frequencies. This can be used to excite various control surfaces in parallel, shorten the excitation time that would be required with an excitation in series.

Figure 5.10 shows a comparison between an optimised multisine input and a conventional double pulse or *doublet* in a simulated excitation of the short-period motion of the GFF subscale demonstrator. While the multisine signal can be applied to both canard and elevons simultaneously, the double pulse needs to be applied separately to avoid correlation and takes twice as much time. It is clear that such an approach cannot be performed manually by the pilot and it requires some degree of automation. The flight-test application for manoeuvre automation, presented earlier, is the key enabler that allows the use of such complex manoeuvres.

Figure 5.10 Simulated excitation of the short-period motion of the GFF subscale demonstrator: optimised multisine input in red, and conventional double pulse or doublet in black.

5.3 Preliminary Results

The methods proposed here were practically tested in various experiments performed mainly with the GFF subscale demonstrator. This platform, shown in Figures 5.11 and 5.11, is a 2-meter jet-powered model that is extensively described in [42]. It represents a challenging case of SFT due to the size of the model and the relatively high flight speed. The experiments with this aircraft were aimed at evaluating the eventual gains in flight testing efficiency.

Figure 5.11 *The Generic Future Fighter (GFF) subscale demonstrator during a flight test. This is a 2-meter, jet-powered platform described in [42].*

Preliminary results show improvements in terms of the amount of information identified against flight time and total resources spent, but also demonstrate an expansion of the previous testing capabilities.

Figures 5.12 and 5.13 show an example of performance data directly reduced from a single 10-minute flight that included dynamic manoeuvres in the pitch axis: total lift coefficient of the aircraft in relation to AOA and deflection of the canard surfaces. At the time of writing, a novel thrust measurement system is being installed on this platform. This system is expected to improve the accuracy of performance estimations such as this one; estimations which are currently based on corrected static thrust measurements.

Regarding the identification of flight-mechanical characteristics, a series of optimised multisine inputs were designed and tested against conventional double-pulse inputs. In both cases, the flight-mechanical models generated with the identified parameters were able to reproduce satisfactorily the short-period motion of real aircraft. Figure 5.14 shows an example of the validation of

Figure 5.12 Cloud of lift data samples obtained during a 10-minute flight which included dynamic manoeuvres in the pitch axis.

Figure 5.13 Example of performance data of the GFF demonstrator obtained during a 10-minute flight which included dynamic manoeuvres in the pitch axis. This data is also compared with earlier numerical estimations.

both models against flight data from a chosen manoeuvre. While both models agree, it should be noted that was acquired using half of the exposure time required by the double pulse input. These results, which are discussed in more detail in paper [III], suggest that the use of simultaneous multisine inputs could be highly beneficial for flight testing of RPA within VLOS. Perhaps, the efficiency of this technique could be further improved by incorporating an on-line monitoring method such as the one proposed in [128].

Figure 5.14 Validation of the short period models identified from flight data: model generated with multisine in red, model generated with double pulse in black, and flight data in blue.

6

Flight Data Processing

Taking into consideration the immense amount of information produced during flight testing, it seems evident that it is needed to count on specific tools that expedite or even automate parts of the data post-processing. Subscale Flight Testing (SFT) is not an exception: the data acquisition system described earlier logs more than 100 parameters at non-synchronised, variable rates that range from 100 Hz to 1 Hz. A single 10-minute flight produces thousands of raw samples that need to be synthesised and interpreted to enable a rational analysis of the experiment.

As an essential part of the investigation of the SFT method, and in parallel with the development of a data acquisition system, this work also entailed the integration or development of the necessary tools for data-processing. In order to be consistent with the *low-cost* approach, expensive commercial-software licenses needed to be avoided. None of the available solutions found in 2015 was appropriate for this particular use, nor allowed open and simple expansion possibilities. Therefore, a new set of tools were developed from scratch using MATLAB; a familiar environment for both academy and industry with a reasonable license cost.

6.1 The ALAN scripts

Aircraft Log Analysis (ALAN) is the rather unimaginative name of a family of scripts and functions written in MATLAB for supporting SFT-data processing at Linköping University. The main purpose of this tool is to ease the verification, transformation, integration, visualisation, and eventual extraction of flight data in an appropriate format for subsequent use with other analysis tools. With respect to the generic modelling process shown in Figures 4.1 and

5.1, this step would be somewhere between the measurement block and the beginning of the parameter identification cycle.

These scripts have been written to fit the specific characteristics and needs of the data acquisition system and the testing methods described earlier. Nevertheless, the structure of the program has been designed in a way that makes it easily compatible with other systems, models, or any sources of flight data. Figure 6.1 tries to summarise the program flow. The compatibility between different aircraft models, different versions of the data acquisition system, or different arrangements of sensors is maintained through the use of configuration files. These files contain the information needed to map and transfer the system-specific variables into the standard variables and units in which the program works. In this way, the program or the flying platforms can also be developed independently.

Figure 6.1 Simplified program flow showing how flight data is processed in ALAN.

6.1.1 Filtering and Plotting

Once the flight data has been imported and formatted, the program offers a choice between multiple tasks. These usually start with signal conditioning options, such as analysis of the spectral density and filtering. The program can display periodograms for the desired signals and then let the user choose what kind of filter to apply. It is also possible to introduce a customised filter or to use other filters available in MATLAB.

Furthermore, the user is offered multiple plotting options. An automatic detection of take-off and landing manoeuvres is used to suggest a pre-selected range of time for visualisation, although the user may select any time segment of interest. These plots can be explored with the usual plot-visualisation tools available in the MATLAB interface.

6.1.2 Animated Flight Reconstruction

It is sometimes convenient to reconstruct and visualise dynamically certain parts of the flight. ALAN has currently two functions that allow animated visualisation of the logged flights. The first one, shown in Figure 6.2, is designed to give a general overview of the aircraft in its flight envelope.

Figure 6.2 *Animated visualisation of flight parameters in ALAN.*

The second one, shown in Figure 6.3, features a 3D model of the aircraft with moving control surfaces. This 3D model reproduces the chosen segments of the flight at the desired speed. The measured angles of incidence of the flow, or

wind vector, are also visualised. Several options to customise the reproduction or to capture a video movie are also offered.

Figure 6.3 Virtual reconstruction of the aircraft motion in ALAN. The 3D-model has moving control surfaces and displays the measured flow incidence vector.

6.1.3 Export of Manoeuvres

ALAN also offers an export function in which the desired manoeuvre or time segments can be selected interactively on the plot and packed in multiple formats. Automatic selection, based on the time flags left by the Lua flight-test application described in Section 5.2.3, is also possible. Further, the user can refer to a text file in which the desired time segments are already specified; a useful option when multiple exports of the same segments are desired.

Figure 6.4 Interactive selection of manoeuvres for exporting to other tools.

7

Discussion

As described in Section 1.2, this thesis builds on from the idea that low-cost Subscale Flight Testing (SFT) could play two different roles in the conceptual design phase: first, contributing to the development and demonstration of new technologies; and second, complementing conventional estimation tools and generating confidence during the concept evaluation process.

To further understand the role of the physical and practical constraints, Chapter 3 explores the scaling principles that apply to the most common scaling methods used in aeronautics: aerodynamic, dynamic, aeroelastic, and the newly named *demonstrative* scaling. The analysis reveals that accurate estimations of full-scale characteristics are theoretically possible for a wide range of different phenomena, although these possibilities are substantially reduced when taking into account practical aspects such as model weight, manufacturing constraints, and operating limitations. The discussion is however open with respect to the role of scaling laws in the demonstration of technology: the relevant physical phenomena may dictate in each case what are the similarity conditions to be met, and hence they may lead to different scenarios and other practical limitations.

Moreover, one of the main factors which impact upon the capabilities of SFT is the cost. The cost of both producing and operating a subscale platform plays a central role in this thesis since it differentiates the traditional use of SFT, illustrated by the numerous big-budgeted projects seen in the literature, and the relatively new low-cost approach examined here. Quantifying precisely these costs and benchmarking against other projects is an arduous task since too many different factors are involved and these specifications are rarely published in detail. Instead, the approach followed here was to define a boundary for what can be considered *low-cost* SFT and to explore the available capabilities through a practical case study.

This practical approach was useful to identify the real needs for equipment and instrumentation as well as to evaluate the potential of available Commercial Off-The-Shelf (COTS) components in this environment. Chapter 4 describes

Figure 7.1 A “virtuous circle” (or “vicious”, perhaps?) of information: a deep understanding of the expected phenomenon is necessary in order to design an appropriate subscale experiment, that in return will reveal more information about the former.

how a suitable data acquisition system is assembled; an example which may serve as a proof of feasibility.

Moreover, Chapter 5 explores how the practical obstacles of remote flight testing could be managed in an economical yet efficient way. The proposed methods should be seen, however, as an example more than as a general rule: mission design and testing methods are often a direct consequence of specific test requirements and case-dependent risk assessment.

Additionally, Chapter 6 shows that appropriate software tools to analyse and visualise flight data can be also developed within a low-cost environment.

However, another angle on this debate suggests that, although the chosen case study is relevant for the empirical evaluation of the initial hypothesis, it does not cover a sufficiently wide range of applications. Acknowledging this point, general conclusions should be drawn carefully.

The quality of the data gathered during the practical experiments suggests that low-cost SFT may be a valid first-cut technical tool comparable to basic numerical methods. However, it was not possible to assess the correlation between the aerodynamic and flight-mechanical parameters estimated with this method and those measured in wind tunnel and full-scale flight. As mentioned in Section 1.3, no real full-scale vehicles were available to benchmark results against. Moreover, most of the experiments were aimed at evaluating the capabilities of systems and methods at a high level, and thus, the importance of highly accurate calibration, measurements and estimations were relegated to a secondary level.

It may be argued that, as in many other experimental methods, the quality of the measured data is often linked to the quality of the test instrumentation and hence it could be associated directly to cost. In such a case, it may be assumed that the quality of the measured flight data, and perhaps the estimations made from these, could be easily improved upon upgrade of the test instrumentation.

This debate about accurate predictions identifies an interesting viewpoint on the relative value of the knowledge gained through SFT: Experts in the field of experimental design methods such as Barlow [55] admit that, although accurate quantitative predictions are always the most desirable achievement, much design work is considered already successful if improvements are achieved, i.e. regardless of whether the methods used provide absolute accuracy in predicting all performance quantities of interest [55].

In contrast to most of the points discussed earlier, another line of thought on SFT defends that the experimentation with physical models should also be valued from a more conceptual and didactic perspective. Contemporary aircraft development programmes are scarce, follow cycles of several decades and not many engineers experience more than one first-flight during their entire careers. Considering this, several authors highlight that SFT gives an opportunity for designers to see their creations fly and provides additional benefits in terms of experience, morale and confidence [3, 34, 51].

In a similar direction, it is also noteworthy the ability of SFT to reveal unforeseen design problems that might not have been detected in the virtual or analytical domains [3, 5]. These points show that the non-quantifiable information provided by SFT may also play a relevant role during the conceptual design process, and therefore, these aspects should also be taken into account when judging the potential of this method in modern aircraft design.

8

Conclusion

Both the theoretical review and the practical experiments described in this thesis are aimed at increasing the comprehension and knowledge of the Subscale Flight Testing (SFT) method in order to identify and evaluate its potential applications in a modern context. The results achieved support the idea that it is possible to find technical solutions to conduct SFT at research level with low costs, and that the capabilities achieved at such level are sufficient to study certain relevant problems for contemporary aircraft design. The experiments carried out here already suggest two examples of possible applications: studying the feasibility and potential issues of an unconventional configuration, and evaluating innovative techniques intended for full-scale applications such as simultaneous multisine excitation for system identification.

The data gathered during these experiments seems to be comparable to that obtained from numerical analysis and simulation tools which, in most of the cases analysed here, benefit from (become augmented by) the complementary real-world inputs in terms of adjustment and credibility. At the present moment, however, no comparison can be provided between the aerodynamic and flight-mechanical parameters estimated via SFT and those measured in wind tunnel and full-scale flight, beyond what it is already available in the literature.

Nevertheless, the observations suggest that SFT may still reduce uncertainty regardless of whether it provides absolute accuracy in predicting all performance quantities of interest. This asset, already exploitable even with very limited resources, may in fact be considered as the main strength of the subscale approach.

To recapitulate, the research questions formulated in Section 1.2 may be answered as follows:

RQ1: The capability of SFT for providing accurate aerodynamic measurements at a relatively low cost is limited to incompressible flow problems in which the phenomenon of interest does not present a significant sensitivity to Reynolds number, and it is further constrained by the natural

atmospheric conditions near the ground. Expanding the envelope by increasing the scale factor, flight speed and altitude translates into a quick escalation of costs; a case in which other tools might become more convenient. In any case, accurate measurements of drag are technically difficult and may be better obtained by other means.

SFT presents better opportunities for the study of dynamic problems, especially those involving low-subsonic flight speeds since compressibility effects could be safely disregarded. Nevertheless, the choice of scale factor is strongly limited by the prescribed model weight and inertia requirements, as well as the speed of the model responses. All these factors may have important consequences in the manufacturing and testing costs.

Similar limitations are found in aeroelastic problems, where the previous issues are added to structural and stiffness constraints. In this case, balancing the scaling requirements to reproduce problems of interest such as BFF may not be possible within the normal flight envelope of a subscale model. In this case, it seems more interesting to accept a certain degree of dissimilarity and to explore the problem of interest within a practical flight envelope, but keeping awareness of the possible differences with a full-scale vehicle.

In fact, leaving aside the conventional similarity conditions, it may be argued that one of the most interesting capabilities of modern SFT is the ability to economically test and demonstrate new technology in a relevant flight environment. With modern capabilities, this method becomes a useful tool for increasing Technology Readiness Level (TRL) with a minimum risk. This kind of scaling method, designated here *demonstrative scaling*, does not necessarily require a rigorously scaled model. Instead, the design of the experiment will depend on the nature and scalability of the technology of interest and the possibilities of finding relevant flight conditions for its evaluation.

RQ2: The current price-performance ratio of low-power microprocessors and solid-state sensors is certainly reaching interesting levels: In this thesis, a complete data acquisition system could be assembled under 1000 Euro of total hardware and software costs. The results obtained from this system indicate that this type of low-cost instruments may bridge the gap between amateur and flight-certified professional hardware by providing sufficient performance for research and development purposes. The obtained signals could be processed and analysed using codes written in a common programming environment and using ordinary workstations. Nevertheless, the requirements for hardware and software are generally determined by the specific characteristics of the intended study, and thus, any generalisation should be done cautiously.

RQ3: It can be concluded that it is possible to conduct productive SFT experiments flying the test aircraft within Visual Line-Of-Sight (VLOS); a type of operation that requires considerably fewer resources than any other option. The severe operational limitations can be, to some extent, compensated with specifically developed techniques to improve testing capabilities and data acquisition efficiency. Some cost-effective examples, such as a relatively simple approach to manoeuvre automation, are proposed in this thesis. On the other hand, the infrastructure needed for this type of operation has shown to be uncomplicated with respect to human resources and facilities. A proposed Concept Of Operations (CONOPS) with only three operators has been implemented with good results in terms of productivity and safety.

9

Review of Papers

Paper I

Design and Testing of a Low-Cost Flight Control and Data Acquisition System for Unstable Subscale Aircraft (2016)

This paper investigates a low-cost solution for providing small, free-flying models with control augmentation and data acquisition capabilities. First, the performance of inexpensive, hobbyist-type COTS equipment is evaluated on different test-beds. A complete system architecture, comprised of both COTS and custom-made components, is proposed. The system is then modelled and its capabilities are incrementally explored using simulation and real flight tests. Although it is outside the main focus of this paper, a first generation of data processing and visualisation codes is also developed at this point. It is noteworthy that, during the following years, the importance of the data acquisition capabilities were prioritised over the control augmentation functions for the larger, jet-powered platforms. The system proposed here was evolved into a more capable data acquisition system without the need of a dedicated data logger, instead of what was initially proposed in this paper.

Paper II

Subscale Flight Testing of a Generic Fighter Aircraft (2016)

This paper gives an overview of the experimentation done with the GFF demonstrator up to 2016. Besides commenting the characteristics of this aircraft, the paper describes how the data acquisition system, developed initially in paper [I], is integrated in this particular platform. The flight testing methods and procedures used at that time, as well as some difficulties encountered, are also described. When compared to paper [III], the reader will note that some of

the testing methods and the capabilities of the data acquisition system were improved later. Two examples of these are the method to automate test manoeuvres, and the improved logging frequency in most channels including a direct sampling of the control surface deflections. Lastly, this paper also describes some improvements regarding data processing and visualisation tools.

Paper III

Methods for efficient flight testing and modelling of remotely piloted aircraft within visual line-of-sight (2018)

In the first place, this paper introduces briefly the current regulatory context for the operation of RPAS and motivates the choice of flight testing within VLOS based on its major cost advantages. Due to the severe limitations in airspace and flight time, a special testing methodology is needed. Various methods and procedures, refined during all previous flight testing campaigns, are suggested. Among these, the paper presents a novel method for commanding automatically pre-programmed excitation manoeuvres without the need of a closed-loop flight controller or an on-line ground station. This enables the study of complex, highly-efficient excitation signals such as multisines. Furthermore, the paper presents an experiment in which a multisine input is used to identify the longitudinal dynamics of the aircraft in less exposure time than that of a conventional manoeuvre.

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