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Introduction

Flight testing is seemingly the stuff of legends, with tales of derring-do and bravery, spearheaded by great pilots such as Yeager, Armstrong, Glenn, and others. But what exactly is flight testing all about? What is being tested, and why? What's the difference between a test pilot and a flight test engineer? Is flight testing an inherently dangerous or risky activity?

With this book, we hope to show that flight testing is both exciting and accessible – we hope to make flight testing understandable and achievable by the typical undergraduate aerospace engineering student. The basic principles of flight testing can be explored in any aircraft, all the while remaining safely well within the standard operating envelope of an aircraft. This book will introduce students to the principles that experienced flight test engineers work with as they evaluate new aircraft systems.

Flight testing is all about determining or verifying the performance and handling qualities of an aircraft. These flight characteristics may be predicted in the design and development stages of a new aircraft program, but we never really know the exact capabilities until the full system is flown and tested. Most aircraft flight testing programs are focused on airworthiness certification, which is the rigorous demonstration of all facets of the flight vehicle's performance and handling characteristics in order to ensure safety of flight.

We also wish to highlight that most flight testing should not incur the levels of risk and danger that we associate with the great test pilots of the 20th century. Their bravery was indeed laudable, since they ventured into flight that no human had done before, such as breaking the "sound barrier" or being the first person to walk on the Moon. But, if done correctly, flight testing should be a methodical process where risks are managed at an acceptable level, where human life and property are not exposed to undue risk. Even more hazardous flight testing such as flutter boundary determination or spin recovery should be done in a methodical, well-controlled manner that mitigates risk. In fact, most flight testing, at least to an experienced professional, can be almost mundane (Corda 2017).

Nor is flight testing an individualistic activity where an intrepid pilot relies solely on their superlative piloting skills to push the aircraft to its limits, as suggested by the caricature in Figure 1.1. Quite the contrary, flight testing is a team effort with many individuals carefully contributing to the overall success of a flight testing program (see Figure 1.2). There is, of course, a pilot involved whose job it is to fly the aircraft as precisely and accurately as possible to put the aircraft through the necessary maneuvers to extract the needed performance or handling data. If an aircraft can carry more than just the pilot, then there is almost always a flight test engineer on board. The flight test engineer is responsible for preparing the plan for the flight test and for acquiring the data in flight while the pilot puts the aircraft through the required maneuvers. Beyond the role of the flight test engineer, there are many others involved – including those who monitor systems and downlinked data on the ground, data analysts who post-process and interpret

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Figure 1.1 The caricature view of flight test is of an individualistic, cowboy-like, rugged test pilot who single-handedly defies danger. Here, Joe Walker playfully boards the Bell X-1A in a moment of levity. Source: NASA.

Figure 1.2 A more realistic view of the people behind flight testing – a team effort is required to promote safety and professionalism of flight. Depicted here is the team of NACA scientists and engineers who supported the XS-1 flight test program. Source: NASA.

the data after the test is complete, and program managers who set the strategic direction for the program and make budgetary decisions.

Flight testing is a critical endeavor in the overall design cycle of a new aircraft system. The main objective is to prove out the assumptions that are inherent to every design process and to discover any hidden anomalies in the performance of the aircraft system. Aircraft design typically proceeds by drawing upon historical data to estimate the performance of a new aircraft concept, but there is always uncertainty in those design estimates. The initial stages of design have very crude estimates made for a wide range of parameters and theories applied to the design. Over time, the design team reduces the uncertainty in the design by refining the analysis with improved design tools and higher-fidelity (more expensive!) analysis, wind tunnel testing, and ground testing of functional systems and even the entire aircraft. But, then the moment of truth always comes, where it is time for first flight of the aircraft. It is at this point that the flight test team documents the true performance of the airplane. If differences arise between actual and predicted performance, minor tweaks to the design may be needed (*e.g.*, the addition of vortex generators on the wings). Also, the insight gleaned from flight testing is documented and fed back into the design process for future aircraft.

This chapter will provide a brief overview of the flight testing endeavor through a historical anecdote that illustrates the key outcomes of flight testing, how flight testing is actually done, and the roles of all involved. Following this, we'll take a look at the various kinds of flight testing that are done, with a particular emphasis on airworthiness certification of an aircraft, which is the main objective of many flight testing programs. We'll then conclude this chapter with an overview of the rest of the book, including our objectives in writing this book and what we hope the reader will glean from this text.

1.1 Case Study: Supersonic Flight in the Bell XS-1

A great way to learn about the essential elements of a successful flight test program is to look at a historical case study. We'll consider the push by the Army Air Forces (AAF) in 1947 to fly an aircraft faster than the speed of sound. Along the way, we'll pick up some insight into how flight testing is done and some of the values and principles of the flight test community.

At the time, many scientists and engineers did not think that supersonic flight could be achieved. They observed significant increases in drag as the flight speed increased. On top of that, there were significant loss-of-control incidents where pilots found that their aircraft could not be pulled out of a high-speed dive. These highly publicized incidents led some to conclude that the so-called "sound barrier" could not be broken. We now know, however, that this barrier only amounted to a lack of insight into the physics of shock–boundary layer interaction, shock-induced separation, and the transonic drag rise, along with a lack of high-thrust propulsion sources to power through the high drag. Scientific advancements in theoretical analysis, experimental testing, and flight testing, along with engineering advancements in propulsion and airframe design, ultimately opened the door to supersonic flight.

In a program kept out of public sight, the U.S. Army Air Forces, the National Advisory Committee for Aeronautics (NACA, the predecessor to NASA), and the Bell aircraft company collaborated on a program to develop the Bell XS-1 with the specific intent of "breaking the sound barrier" to supersonic flight. (Note that the "S" in XS-1 stands for "supersonic"; this letter was dropped early in the flight testing program, leaving us with the commonly known X-1 notation.) The XS-1 (see Figure 1.3) was a fixed-wing aircraft with a gross weight of 12,250 lb, measured 30-ft

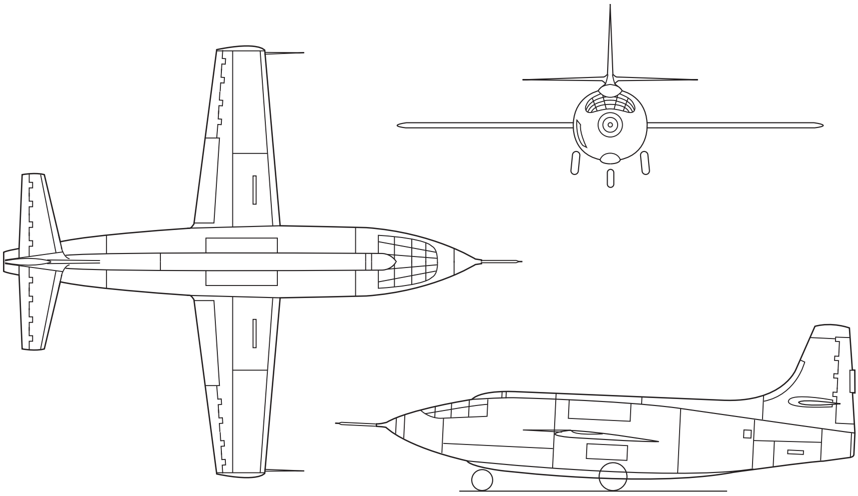

Figure 1.3 Three-view drawing of the Bell XS-1. Source: NASA, X-1/XS-1 3-View line art. Available at http://www.dfrc.nasa.gov/Gallery/Graphics/X-1/index.html.

11-in. long, had a straight (unswept) wing with an aspect ratio of 6.0 and a span of 28 ft, and an all-moving horizontal tail (a detail that we'll soon see was important!). The XS-1 was powered by a four-chamber liquid-fueled rocket engine producing 6000 lb of thrust. The overarching narrative of the program is well documented in numerous historical and popular sources (*e.g.*, see Young 1997; Gorn 2001; Peebles 2014; Hallion 1972; Hallion and Gorn 2003; or Wolfe 1979), but we'll pick up the story in the latter stages of the flight test program at Muroc Army Airfield, positioned on the expansive Rogers Dry Lake bed that is today the home of Edwards Air Force Base and NASA Armstrong Flight Research Center.

The XS-1 had an aggressive flight test schedule, with not too many check-out flights before going for the performance goal of supersonic flight. The extent of the test program was actually a matter of contentious debate between the AAF, the NACA, and Bell. In the end, Bell dropped out of the mix for contractual and financial reasons, and the NACA and AAF proceeded to collaborate on the flight test program. But the continued collaboration was not without tension. The AAF leaders and pilots continually pushed for an aggressive flight test program, making significant steps with each flight. The NACA, on the other hand, advocated for a much slower, methodical pace where substantial data would be recorded with each flight and carefully analyzed before proceeding on to the next boundary. In the end, the AAF vision predominantly prevailed, although there was a reasonable suite of instrumentation on board the aircraft. The XS-1 was outfitted with a six-channel telemeter, where NACA downlinked data on airspeed, altitude, elevator position, normal acceleration, stabilizer position, aileron position, and elevator stick force, along with strain gauges to record airloads and vibrations (Gorn 2001, p. 195). On the ground, the NACA crew had five trucks to support the data acquisition system – one to supply power, one for telemetry data, and three for radar. The radar system was manually directed through an optical sight, but if visual of the aircraft was lost, the radar system could be switched to automatic direction finding (Gorn 2001, pp. 187–188).

To lead the flying of the aircraft toward the perceived "sound barrier," the AAF needed a pilot with precision flying capabilities, someone who was unflappable under pressure, and someone with scientific understanding of the principles involved. The Army turned to Captain Charles E. "Chuck" Yeager – a young, 24-year-old P-51 ace from World War II – for the honor and responsibility of being primary pilot. According to Colonel Albert Boyd who selected him, Yeager had impeccable instinctive piloting skills and could work through the nuance of the aircraft's response to figure out exactly how it was performing (Young 1997, p. 41). Not only could he fly with amazing skill, but the engineering team on the ground loved him for his postflight debriefs. Yeager was able to return from a flight and relate in uncanny detail exactly how the aircraft responded to his precise control inputs, all in a vernacular that the engineering staff could immediately appreciate (Peebles 2014, p. 29). But it wasn't just Yeager doing all of the work – he had a team around him. Backing him up and flying an FP-80 chase plane was First Lieutenant Robert A. "Bob" Hoover, who was also well known as an exceptional pilot. Captain Jackie L. "Jack" Ridley, an AAF test pilot and engineer with an MS degree from Caltech, was the engineer in charge of the project. Others involved included Major Robert L. "Bob" Cardenas, pilot of the B-29 Superfortress carrier aircraft and officer in charge, and Lieutenant Edward L. "Ed" Swindell, flight engineer for the B-29. Backing up these AAF officers was Richard "Dick" Frost, a Bell engineer and test pilot who already had flight experience in the XS-1 and got Yeager up to speed on the intricacies of the aircraft. This cast of characters is depicted in Figure 1.4.

Beyond this core group of military professionals was a team of NACA scientists and engineers led by Walt Williams (see Figure 1.2). This team was focused predominantly on understanding the flight physics in this exploratory program, providing deep technical insight and support to the Air Force crew. Yet, this objective was inherently at odds with the AAF's stated desire to push to supersonic flight as quickly and safely as possible. This tension was aptly described by Williams: "We were enthusiastic, there is little question. The Air Force group – Yeager, Ridley – were very, very enthusiastic. We were just beginning to know each other, just beginning to work together. There had to be a balance between complete enthusiasm and the hard, cold facts. We knew that if this program should fail, the whole research airplane program would be set back. So, our problem became one of maintaining the necessary balance between enthusiasm and eagerness to get

Figure 1.4 The Air Materiel Command XS-1 flight test team, composed of (from left to right): Ed Swindell (B-29 Flight Engineer), Bob Hoover (XS-1 Backup and Chase Pilot), Bob Cardenas (Officer-in-charge and B-29 Pilot), Chuck Yeager (XS-1 Pilot), Dick Frost (Bell Engineer), and Jack Ridley (Project Engineer). Source: U.S. Air Force.

the job completed with a scientific approach that would assure success of the program. That was accomplished" (Gorn 2001, pp. 194–195).

In the run-up to the first supersonic flight, the team carefully pushed forward. On Yeager's first powered flight on August 29, 1947, he accelerated up to Mach 0.85, exceeding the planned test point of Mach 0.8. This negated NACA's need to acquire telemetered data in the Mach 0.8–0.85 range, leading to further tension between Yeager and Williams. In Yeager's words, "They [the NACA engineers and technicians] were there as advisers, with high-speed wind tunnel experience, and were performing the data reduction collected on the X[S]-1 flights, so they tried to dictate the speed in our flight plans. Ridley, Frost, and I always wanted to go faster than they did. They would recommend a Mach number, then the three of us would sit down and decide whether or not we wanted to stick with their recommendation. They were so conservative that it would've taken me six months to get to the [sound] barrier" (Young 1997, p. 51 – quoted from Yeager and Janos (1985), p. 122).

Yeager was admonished by Colonel Boyd to cooperate more carefully with the NACA technical specialists and to follow the test plan. This led to careful preflight briefings that, while Yeager considered to be tedious, were essential to flight safety and accomplishment of the test objectives. At each briefing, Williams would review the lessons learned from the previous flight and detail the objectives of the upcoming mission (Gorn 2001, pp. 195–196).

As Yeager flew at progressively higher flight speeds, he noticed significant changes in the trim condition of the aircraft. At certain Mach numbers, the trim condition would change nose-up, and at other Mach numbers it would trend toward nose-down, all accompanied by buffeting at various flight conditions. For example, on one flight at Mach 0.88 and 40,000 ft, Yeager was unable to put the aircraft into a light stall (even with the stick full aft), due to the lack of control authority. Then, on October 10, 1947, Yeager piloted another mission in a series of powered flights to ever-higher Mach numbers to test the response of the aircraft in this untested regime. After accelerating up to an indicated Mach number of 0.94 at an altitude of 40,000 ft, Yeager found that he had lost virtually all pitch control! He moved the control stick full fore and aft, yet obtained very little pitch response. Fortunately, the XS-1 was still stable at this flight condition, if not controllable. At this point, Yeager cut off the engines and came back for a landing on the expansive Rogers lakebed (Young 1997).

All of these various anomalies were due to compressibility effects, which were only poorly understood at the time. As the aircraft exceeded the critical Mach number, shock waves would form at various locations on the aircraft body. Furthermore, these shock waves could move substantially, with only a minor adjustment in freestream Mach number. Since there is a significant pressure gradient across a shock wave, this could result in dramatic changes in the forces and moments produced on control surfaces, and the strong pressure gradient across the shock would often lead to boundary layer separation. Thus, if a shock happened to be present at a hinge line for the elevator, the shock-induced boundary layer separation would create a thick unsteady wake flow over the elevator, causing the dynamic pressure on this control surface to drop dramatically and the elevator to lose effectiveness. With some foresight, researchers at NACA and designers at Bell anticipated this eventuality and designed the XS-1 to enable pitch control by moving the incidence angle of the entire horizontal tail (rather than inducing pitch changes using the elevator alone). So, as Yeager and Ridley discussed the phenomena occurring on October 10 and earlier, Ridley encouraged Yeager to adjust the horizontal tail angle of incidence to achieve pitch control, instead of using the elevator.

The plan for the next flight was to go for it – Yeager's intent was to fly supersonic. However, with the technical uncertainty associated with loss of elevator control and shock-induced buffeting, the NACA engineering team admonished Yeager to not exceed Mach 0.96 unless he was completely certain that he could do so safely. Beyond the NACA team, however, Jack Ridley was the one whom Yeager trusted the most. Ridley thought Yeager would be just fine controlling pitch with the moving horizontal tail, actuating it in increments of a quarter or a third of a degree to achieve pitch control without using the elevator. Ridley explained, “It may not be much, and it may feel ragged to you up there, but it will keep you flying” (Young 1997, p. 56). Yeager trusted Ridley implicitly – much more so than the NACA team. He later recounted, “I trusted Jack with my life. He was the only person on earth who could have kept me from flying the X [S]-1” (Young 1997, p. 56).

So, on the morning of October 14, 1947, Yeager set out with his team to fly faster than Mach 1. With Cardenas at the controls of the B-29, the Superfortress carried the Bell XS-1 up to altitude. On the way up, Bob Hoover and Dick Frost joined up in formation in their FP-80s. Hoover positioned himself in the “high chase” position: 10 mi ahead of the B-29 at an altitude of 40,000 ft, to give Yeager an aiming point as he climbed and accelerated in the XS-1. Frost joined up slightly to the right of and behind the B-29 in order to observe the rocket firing and drop of the XS-1.

When everyone was ready, Cardenas put the B-29 in a slight dive and started a countdown: “10-9-8-7-6-5-3-2-1” (yes, he skipped “4”!, as he often skipped a number on these flights) and pulled the release mechanism at 10:26 a.m. an altitude of 20,000 ft and an airspeed of 250 knots. This airspeed was slightly lower than planned, causing the XS-1 to nearly stall. Yeager pitched the nose down to regain airspeed and then lit all four burners to rapidly accelerate upward. As he breezed past the high-chase FP-80, Hoover was able to snap the world-famous photo of Yeager’s flight (Figure 1.5) as the XS-1 continued going faster and higher. Yeager then shut down two of the rocket chambers in order to keep the vehicle’s acceleration in check. Accelerating through Mach 0.83, 0.88, and 0.92, he tested the aircraft’s response to horizontal stabilizer control. With the small increments of a quarter or a third of a degree that Ridley recommended, Yeager was able to maintain effective control of the aircraft. Then, as Yeager recounted in his postflight report: “At 42,000’ in approximately level flight, a third cylinder was turned on. Acceleration was rapid and speed increased to .98 Mach_i. The needle of the machmeter fluctuated at this reading momentarily, then passed off the scale. Assuming that the off-scale reading remained linear, it is estimated that 1.05 Mach_i was attained at this time. Approximately 30% of fuel and lox remained when this speed was reached and the motor was turned off” (Young 1997, p. 75).

Figure 1.5 Yeager accelerates in the Bell XS-1 on his way to breaking the “sound barrier” on October 14 1947. Source: NASA.

Yeager had done it! As mentioned in his postflight report, his Machmeter indications were a bit unusual. In fact, during the flight he radioed: “Ridley! Make another note. There’s something wrong with this Machmeter. It’s gone screwey!” (Young 1997, p. 73). That radio transmission heralded the dawn of a new era in aviation to supersonic speeds and well beyond. After maintaining supersonic flight for about 15 seconds, he shut down the rocket motors, performed a 1-g stall, and descended for a landing on Rogers dry lakebed.

Postflight analysis of the data, including corrections of the Machmeter reading for installation error, revealed that Yeager had reached a maximum flight Mach number of 1.06. A reproduction of this data is shown in Figure 1.6, where the initial jump in total and static pressures heralded the formation of a shock wave in front of the probe tip, causing a loss of total pressure. This is the characteristic “Mach jump” experienced by every Machmeter as the aircraft accelerates to supersonic speeds.

There are a number of interesting and revealing features of this story that can tell us something about flight testing. First, we see that this endeavor was anything but an individual effort. There was a large team with many players involved – pilots, engineers, managers, analysts, range safety officers, and so on. In this particular case, the flight test program was a collaboration between two separate organizations – the AAF was leading the program execution, and were supported by NACA’s technical experts. Even though there was tension between these two groups, they were able to rise above those difficulties to work together in an effective manner to achieve the test objectives.

The source of the tension was inherently due to different test objectives – the AAF crew was tasked with breaking the sound barrier as quickly and safely as possible, while the NACA team was focused on developing a scientific understanding of transonic and supersonic flight, requiring a slower and more methodical approach. Flight test programs sometimes have such competing objectives in mind, which requires deft coordination and program management in order to ensure

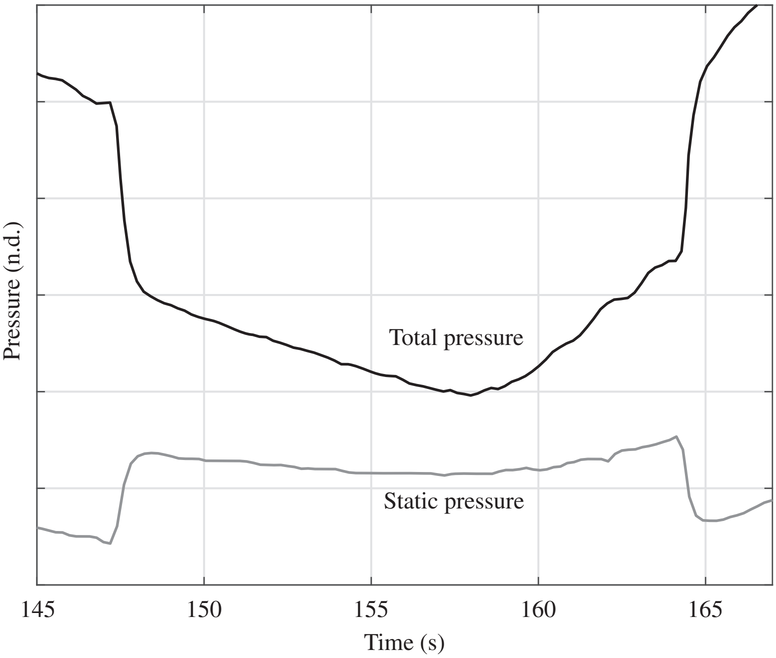

Figure 1.6 Plot of the total and static pressure for the first supersonic flight of the XS-1 on October 14 1947. Source: Data from NASA.

safety of flight and accomplishment of the test objectives. There is always a tension between programmatic needs, budget, and safety.

Another hallmark of successful flight testing is the careful probing of the edges of the flight envelope. Notice how the team approached the uncertain conditions associated with loss of control and buffeting. They gingerly pushed the Mach limits higher and higher, with the hope that any loss-of-control situation could be quickly recovered from. Despite the accelerated nature of the test program, the team took the time to carefully analyze the data and debrief after each flight. This was essential for gleaning insight from each test condition and informing the next step in the flight test program. They took an incremental buildup approach – starting from low-risk flights with known characteristics and carefully advancing to higher-risk flights, where the flight characteristics were unknown and potentially hazardous.

Also note how the aircraft was instrumented beyond what a normal production aircraft would have been. In fact, the record-setting XS-1 (the first airframe built) was only lightly instrumented compared to its sister ship, the second airframe off the production line, which was targeted for a much more detailed exploration of supersonic flight by the NACA team. This instrumentation is critical for understanding exactly what is happening during flight and preserving a record for post-flight analysis. The analytical work was done by a large team of engineers, technicians, and, in that day, human "computers" who did many of the detailed computations of the data (see Figure 1.2).

After some initial renegade flying by Yeager, the flight test team settled into a rhythm of carefully planned and executed flights. Before each flight they carefully planned the objectives and specific maneuvers to fly on the next mission. The injunction was that the flight must proceed exactly as planned, with specific plans for various contingencies and anomalies. This culture of flight testing is absolutely essential for the safety and professionalism of the process. One common phrase captures this mentality of flight testing: "plan the flight, and fly the plan."

This initial foray into exploring the flight testing program of the XS-1 illustrates many of the hallmarks of flight test programs. We'll next discuss some of the different kinds of flight testing being done today. Clearly, not every flight test program is as ambitious or adventurous as the XS-1 program, but a common objective is to answer the remaining unknown questions that are always present in an aircraft development program, even after rigorous design work backed up by wind tunnel testing and computational studies.

1.2 Types of Flight Testing

There are several different kinds of flight testing, driven by the objective of a particular program. These motivations include scientific research, development of new technologies or experimental capabilities, evaluation of operational performance, or airworthiness certification of new aircraft for commercial use. Other kinds of flight tests include production flight test (first flight of a new airframe of an already certified type, to verify compliance with design performance standards), systems flight test (new systems installed, new external stores on a fighter aircraft that must be tested for separation, new avionics systems), and post-maintenance test flight. Here, we'll focus our attention on flight testing for scientific research, assessment of experimental technologies, developmental test and evaluation, operational test and evaluation, and airworthiness certification programs. Other perspectives on the different kinds of flight testing are provided by Kimberlin (2003), Ward et al. (2006), or Corda (2017).

1.2.1 Scientific Research

In many instances, the highest-quality scientific research can only be done in actual flight. Even though wind tunnels are commonly available, results from these facilities are always limited in some way – facility effects such as streamwise pressure gradients in the test section, wall boundary layer effects, test section blockage, turbulence intensity level, constraints on model size, lack of Mach and/or Reynolds scaling, etc. are always present (see Tavoularis 2005 or Barlow et al. 1999 for a discussion of wind tunnels and their limitations). Similarly, computational fluid dynamics simulations are inherently limited in their ability to model viscous, unsteady separated flows, particularly when the model – such as a full aircraft – is large (see Cummings et al. 2015 for the limitations on computational aerodynamics). Grid resolution, turbulence modeling strategies, and time-accurate solutions will always need validation of some kind. Thus, the ultimate proof of scientific principles associated with flight is to actually conduct experiments in flight.

The range of scientific experiments that can be studied via flight testing can be very broad and conducted by government labs, universities, and industry. University flight test efforts have included Purdue University's development of pressure-sensitive paint (PSP) for in-flight measurements of chordwise surface pressure distribution on an aircraft wing (Figure 1.7). The advantage of PSP is that there is minimal flow intrusiveness, compared to the traditional pressure belts mounted on top of the wing, which are banded and flexible tubes. Furthermore, it is much simpler to instrument the aircraft with PSP, since no tubing has to be run into the fuselage and connected to pressure transducers. In fact, the production Beechjet 400 shown in Figure 1.7 was returned to normal flight under its regular airworthiness certification immediately following flight testing (Lachendro 2000).

Another leading flight test program for scientific research is the University of Notre Dame's Airborne Aero-optics flight research program (Jumper et al. 2015). Researchers at Notre Dame, led by Prof. Eric Jumper and Prof. Stanislav Gordeyev, study approaches for correcting optical aberrations to laser beams propagating through unsteady shear flows and turbulence. Their active correction schemes allow them to focus a laser beam emitted from one aircraft on the fuselage of a target aircraft such as the Dassault Falcon 10 shown in Figure 1.8. These concepts are used for applications ranging from optical air-to-air communications to directed energy for military applications.

The US government is also active with scientific research enabled by flight testing programs. One notable example is NASA's F-18 high alpha research vehicle (HARV). The goal of the first phase of this program was to understand vortex formation, trajectory, and breakdown on the F-18 operated at

Figure 1.7 Inspection of pressure-sensitive paint on Purdue University's Beechjet 400 following a flight test in 1999 (depicted left to right are Hirotaka Sakaue, Brian Stirm, and Jim Gregory). Source: Photo courtesy of Nate Lachendro.

Figure 1.8 Notre Dame's Dassault Falcon 10. Source: U.S. Air Force.

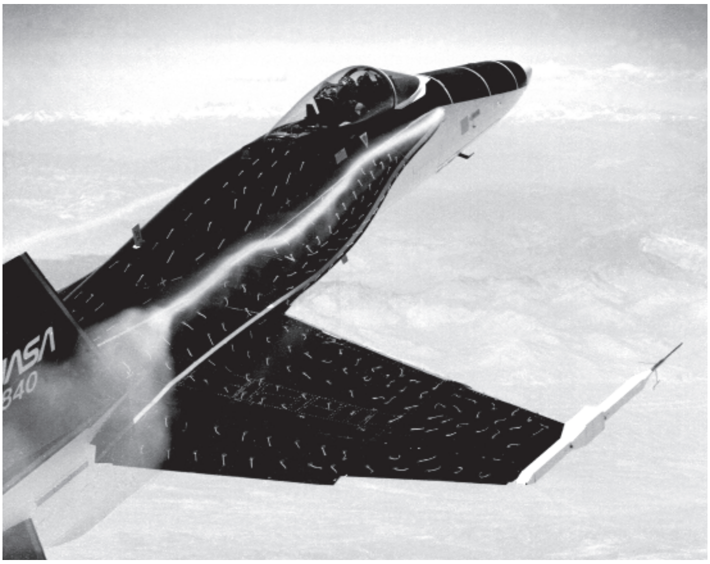

Figure 1.9 Smoke and tuft flow visualization on the NASA F-18 High Alpha Research Vehicle at an angle of attack of 20°. Source: NASA.

high angle of attack. The specially instrumented F-18 had tufts (short pieces of yarn) taped to the top of the wing, smoke tracer particles released from orifices near the nose, dye flow visualization, and hundreds of pressure taps. These various techniques were used to study local flow separation and vortex trajectories. In-flight measurements, shown in Figure 1.9, clearly documented the formation of vortices on the leading-edge extension (LEX) of the F-18 at high angle of attack, the trajectory of these vortices, and the specific location of vortex breakdown. The vortex breakdown phenomenon, when occurring in the vicinity of the aft tail, led to significant tail buffeting and issues with fatigue (see Fisher et al. 1990).

1.2.2 Experimental Flight Test

Now, we turn our attention from basic scientific and engineering studies to development and test of new vehicle concepts. NASA Armstrong Flight Research Center (formerly known as NASA Dryden) has led the way over the years with this type of flight research (for a good historical overview of NASA's many flight research programs, see Gorn 2001 or Hallion and Gorn 2003). This type of flight testing is all about pushing the boundaries of what is possible, through development and demonstration of new flight technologies. Beyond the Bell XS-1 discussed earlier, there are numerous flight research programs that the US Government has conducted (Miller 2001; Jenkins et al. 2003). These cutting-edge aircraft are generally classified as X-planes, with the goal of proving out new technologies or advanced concepts (see Figure 1.10). The Bell XS-1 was the first aircraft in this distinguished lineup, which includes over 60 aircraft (and counting!). Many of these X-planes led to successful production flight vehicles after a period of focused flight testing (see Miller 2001; Jenkins et al. 2003; Corda 2017).

One interesting example is the X-wing project, which had the goal of improving the forward flight speed of helicopters. This interesting vehicle, the Sikorsky S-72 shown in Figure 1.11, is a hybrid between a fixed wing aircraft and a traditional rotorcraft. It could take off vertically like a traditional helicopter, but then its rigid rotors could be stopped mid-flight as the aircraft transitioned from vertical flight to forward flight. Instead of articulating the rotor blades as a traditional helicopter does, the S-72 used compressed air blown from the edges of the blades to achieve lift control (called circulation control – see Reader and Wilkerson 1977 for details). This innovative aircraft from the

Figure 1.10 Early X-planes, including the Douglas X-3 Stiletto (center) and (clockwise, from lower left) Bell X-1A, Douglas D-558-1 Skystreak, Convair XF-92A, Bell X-5, Douglas D-558-2 Skyrocket, and the Northrop X-4 Bantam. Source: NASA.

Figure 1.11 Sikorsky S-72 X-wing testbed aircraft. Source: NASA.

early 1980s has paved the way for high-speed helicopters today, such as the Sikorsky S-97 Raider or the Airbus RACER program.

Vehicle flight testing programs are also pushing into the domain of unmanned aircraft systems (UAS), commonly known as drones. For example, The Ohio State University developed and flight tested the Avanti UAS, which is a 70-lb jet capable of autonomous, unmanned, high-speed flight (Figure 1.12). This flight vehicle featured dual-redundant radio control links and a third independent satellite communications link, to provide robust beyond-line-of-sight flight. Flight research with this vehicle assessed the robustness of the control links, along with adaptive control laws for real-time in-flight system identification (see Warwick 2017; McCrink and Gregory 2021;

Figure 1.12 The Ohio State University's Avanti jet unmanned aircraft system. Source: Photo courtesy of Kamilah King.

or Chapter 16 for details). In the midst of the flight testing program, the Ohio State team set official world records for speed (147 mph) and out-and-back distance (28 mi) of an autonomous unmanned aerial vehicle (UAV), as certified by the Fédération Aéronautique Internationale (FAI) and the National Aeronautic Association (NAA).

1.2.3 Developmental Test and Evaluation

Within the US military, a significant amount of time and energy are invested in development test and evaluation (DT&E) flight testing. This aspect of flight testing involves a careful assessment of how an aircraft flies, including evaluation of aircraft performance, stability, and handling qualities. DT&E also includes performance assessment of new weapons, new software, and new airframes. These tests are centered on assessment of compliance with performance standards and focus on identifying anomalies in new systems. Test pilots (see Figure 1.13) push the performance limits of the system and are often involved in test planning very early in the design cycle. For example, if a new weapon system is designed for an aircraft, the developmental test pilot will evaluate the separation characteristics, compatibility of the new weapon with the aircraft system across a wide range of flight conditions, and evaluation of flutter flight characteristics. This testing and evaluation are done through a gradual build-up approach that minimizes (but does not eliminate) risk.

1.2.4 Operational Test and Evaluation

Operational test and evaluation (OT&E) involves assessment of an air vehicle's performance under representative operational conditions. This often includes operation on different runways under different conditions (*e.g.*, rain, sleet, snow, etc.) or at high-density altitude (high elevation, hot day). Operational testing also involves determination of crosswind limits on landing and taxiing operations. Aircraft manufacturers will also assess aircraft system robustness and reliability under a wide range of extreme weather conditions, including heat, cold, and icing.

Figure 1.13 Maj Rachael Winiecki, a developmental test pilot with the 461st Flight Test Squadron at Edwards Air Force Base, and the first F-35 female test pilot. Also shown is Airman 1st Class Heather Rice, a crew chief with the 412th Aircraft Maintenance Squadron. Source: U.S. Air Force.

1.2.5 Airworthiness Certification

Airworthiness certification is the process by which an aircraft is demonstrated to conform to approved design principles and that it is in a condition for safe operation. But what constitutes safe flight? This generally involves an insignificant hazard to people or property on the ground and minimal hazard to the occupants of the aircraft. Typically, a government's civil aviation authority, such as the Federal Aviation Administration (FAA) in the United States, grants an airworthiness certificate to an applicant submitting reports that document airworthiness for a new aircraft type. This process can be lengthy, involving flight testing to document aircraft performance and demonstrate compliance with safety standards.

In the United States, the regulatory authority for the FAA to certify the airworthiness of light aircraft is Title 14 of the Code of Federal Regulations ("Aeronautics and Space"), Chapter I ("Federal Aviation Administration, Department of Transportation"), Subchapter C ("Aircraft"), Part 23 ("Airworthiness Standards: Normal Category Airplanes") – we'll refer to this as 14 CFR §23 or simply part 23 (U.S. Code of Federal Regulations 2021). Part 23 covers the certification standards for general aviation aircraft, which have a maximum takeoff weight of 19,000 lb or less and carry 19 or fewer passengers. Since the scope of this book focuses on light aircraft, Part 23 is most relevant for our purposes. The subpart that is most relevant for flight testing is Subpart B (14 CFR §23.2100 through §23.2165), which defines the requirements for flight testing of aircraft for airworthiness certification.

Aircraft certified under Part 23 are grouped into different certification and performance levels based on number of passengers that can be carried and flight speed (14 CFR §23.2005), which are summarized in Table 1.1. Each level indicates a higher hazard, and a correspondingly higher bar is set to mitigate the risks associated with those hazards. Aircraft at the higher certification levels and higher performance levels will have higher standards to meet for certification.

Part 23 details the standards of safe flight that must be met for an aircraft to be certified as airworthy by the FAA, organized into broad categories of performance metrics and flight characteristics. Performance metrics include defining limits on the aircraft weight and center of gravity position, the stall speed of the aircraft under various operating conditions, takeoff performance, climb performance, glide performance, and landing distance required. The flight characteristics for certification include demonstration that the airplane is controllable and maneuverable; that the airplane can be trimmed in flight; that it has static and dynamic longitudinal, lateral, and directional stability; that the aircraft has controllable stall characteristics in all maneuvers and that

Table 1.1 Airworthiness certification levels defined by part 23.

Airplane certification levels		Airplane performance levels	
Level 1	Maximum seating configuration of 0–1 passengers	Low speed	Airplanes with a V_{NO} and $V_{\mathrm{MO}} \leq 250$ KCAS (and $M_{\mathrm{MO}} \leq 0.6$)
Level 2	Maximum seating configuration of 2–6 passengers		
Level 3	Maximum seating configuration of 7–9 passengers	High speed	Airplanes with a V_{NO} or $V_{\mathrm{MO}} > 250$ KCAS (and $M_{\mathrm{MO}} > 0.6$)
Level 4	Maximum seating configuration of 10–19 passengers		

V_{NO} = maximum structural cruising speed, V_{MO} = maximum operating limit speed, M_{MO} = maximum operating Mach number, and KCAS represents the units for knots calibrated airspeed.

Source: Based on FAA (2011).

sufficient stall warning is provided; that spins are recoverable; that the airplane has controllable ground handling characteristics; and that vibration and buffeting do not interfere with control of the airplane or cause excessive fatigue. If certification is requested for flight into known icing conditions, then the aircraft performance and handling characteristics must be shown to the same level of safety even in icing conditions. This textbook provides an introduction to the underlying principles for some of these flight tests; more detailed information is available from Kimberlin (2003) or FAA Advisory Circulars (2003, 2011).

While the regulatory framework and overall safety criteria are defined in Part 23, the regulations are intentionally sparse on details on *how* to actually demonstrate compliance for certification. Instead, means of compliance (§23.2010) can be determined by the applicant, subject to approval by the FAA. Typically, the means of compliance is established by a consensus standard. A type certificate applicant for a new light aircraft could demonstrate compliance with a consensus-based industry standard, which has been approved by the FAA. This compliance mechanism is a dynamic and flexible approach (compared to explicitly defining the compliance mechanisms in part 23), since consensus-forming bodies can quickly respond to new technologies and develop consensus standards. One key example of such a body is ASTM International. The ASTM convenes a number of committees, which are populated by representatives from various industry groups, and also includes government (FAA) representatives. The key ASTM committee that covers certification standards for light aircraft is the F44 committee on General Aviation Aircraft and specifically the F44.20 subcommittee on Flight. At the time of writing this book, ASTM F44.20 had published standard specifications for flight test demonstration of aircraft weight and center of gravity, operating limitations, aircraft handling characteristics, performance, and low-speed flight characteristics (ASTM 2017, 2018a, 2018b, 2019a, 2019b). Historical guidance from the FAA is also available for means of compliance with 14 CFR part 23 through nonregulatory advisory circulars (FAA 2003, 2011).

It's important to also be familiar with the historical approaches to airworthiness certification, since there are many aircraft flying today that were certified under older versions of the regulations. Predating certification of general aviation aircraft under part 23, certification was granted under the Civil Air Regulations (from the late 1930s until 1965). Kimberlin (2003, chapter 1) provides a good synopsis of these older regulations and how antique aircraft are still flying under airworthiness certificates granted under the older regulations.

For decades, certification of light general aviation aircraft followed regimented flight testing protocols that were explicitly defined in part 23. Over the years, the part grew more complex as additional safety measures and compliance protocols were codified. The resulting regulation was a rigid document that could not easily accommodate new technologies. For example, part 23 was strictly written to document how a type applicant must demonstrate the performance of internal combustion engines and the associated fuel system. This strict delineation of a compliance pathway was fine when all general aviation aircraft were powered by internal combustion engines running off Avgas. However, there are new propulsion system concepts emerging such as electric motors driven by fuel cells, batteries, or hybrid battery-generator systems, but these could not be certified under the former regimented structure of part 23. Type certificate applicants would have had to demonstrate an equivalent level of safety and obtain waivers, but there was no established and agreed-upon process for doing so. Thus, certification of new technologies such as electric propulsion would have been costly, with an uncertain outcome.

The current certification framework was developed in response to these challenges, leading to a complete rewrite of part 23 in 2016. With the rewrite of part 23, the FAA removed historical designations of various certification categories for airplanes. While these categories no longer exist for new aircraft certifications, any aircraft certified under the old part 23 will retain its category designation. These categories are normal, utility, acrobatic, and commuter. The commuter category is the designation for the largest general aviation aircraft, with a maximum takeoff weight of 19,000 lb, a passenger seating capacity of up to 19, and multiple engines. The normal, utility, and acrobatic categories all have a much lower weight limit of 12,500 lb and a seating capacity of up to 9. Normal category airplanes are approved for normal (routine) flying, stalls (but not “whip stalls”), and routine commercial maneuvers (less than 60° bank). Airplanes certified for utility category are approved for limited aerobatic maneuvers, which may include spins and commercial maneuvers at higher bank angles (up to 90°). Acrobatic category airplanes are approved for acrobatic maneuvers, which is basically any maneuver that a pilot can fly, and found to be safe in the flight testing program. For the normal, utility, and acrobatic categories, a given airplane could be certified for one, two, or all three, with varying operating limitations corresponding to each. Given that there are many aircraft routinely flying today that are well over 60 years old, one can anticipate that these legacy certification categories will persist for quite some time as historical and current aircraft continue flying.

1.3 Objectives and Organization of this Book

Our objective for this book is to provide the reader with an introduction to the exciting world of flight testing of light aircraft and UAS. Within the broad theme of that overarching objective, we specifically seek to:

(1) Provide a solid foundation for the reasons why flight testing is done the way it is. This involves a clear and concise establishment of the theoretical principles. Each equation that is presented here is backed up by physical explanations of the phenomena involved.
(2) Offer aerospace engineering students the context for connecting engineering theory with practice through guided flights in an aircraft. This provides the student with a visceral, empirical way of connecting their theoretical knowledge of flight with practical knowledge. The goal is for the student to develop a tacit understanding of flight beyond the explicit knowledge gleaned in traditional classrooms.
(3) Introduce the concepts and practice of digital data acquisition and signal processing, which is the underpinning of complex industrial and governmental flight test programs. These concepts are typically not taught in the undergraduate aerospace curriculum, but are important for knowing how to acquire and analyze flight test data using advanced, micro-scale sensors and digital data acquisition systems.
(4) Provide an overview of many of the foundational flight test topics encountered in performance flight testing. Individual chapters address each topic in turn, starting with the theoretical basis for that aspect of aircraft performance and moving on to flight test methods for acquiring and analyzing data for each performance metric.

This text is partitioned into two main segments – the first half of the book (Chapters 1–6) deals with preliminary content and fundamental principles, while the second half (Chapters 7–16) covers a series of flight test topics in detail. The flight tests covered here focus predominantly on the performance and stability characteristics of an aircraft. We predominantly focus on light general aviation aircraft and UAVs, since these are accessible to most students, and optimal learning takes place when a student can experience flight testing firsthand. The material is designed to be accessible such that a student can go with a qualified pilot in nearly any general aviation aircraft and acquire meaningful flight test data. Dedicated flight test instrumentation, modifications to the aircraft, or expensive hardware is not required. Thus, many of the flight test methods presented here may be simplified relative to what is done in industry.

Figure 1.14 Ohio State University students Greg Rhodes and Jennifer Haines following turn performance flight testing in a Piper PA-28R at the Ohio State University Airport. Source: Courtesy of Greg Rhodes and Jennifer Haines.

This textbook should not be regarded as a definitive or even advisory source on how to conduct flight testing. Instead, this book should be considered a general introduction to the ideas, scientific principles, theoretical foundations, and some of the best practices associated with flight testing. We provide a mix of aircraft performance theory with flight testing methods. Our goal is to invite the student or practitioner into understanding the physical fundamentals underlying flight testing – this will enable the reader to more fully appreciate why flight testing is done the way it is, to spot errors or problems in theory or procedures, and to know how to adapt established practices to unanticipated circumstances or new vehicle concepts. So, our aim is to provide a general overview and introduction to flight testing: a general idea of the nature of the field and a sound theoretical basis for what is done. We hope that this book will be a good first step as preparation for entry into the flight testing domain, where more detailed methods can be picked up on the way.

Official publications, standards, and advisory documents from the relevant civil aviation authority must be regarded as the definitive source for guidance on how to safely conduct flight testing and how to provide sufficient information to comply with the certification requirements. In the United States, this documentation is primarily found in 14 CFR 23, FAA Advisory Circular 23-8C, and any consensus standards accepted by the FAA (such as standards produced by ASTM International's F44 committee on General Aviation Aircraft). Other helpful sources of procedural and practical information are found in Hamlin (1946), Smith (1981), Stoliker et al. (1996), Stinton (1998), Kimberlin (2003), Ward et al. (2006, 2007), McCormick (2011), Mondt (2014), Corda (2017), and the publicly available flight test guides from the governmental flight test organizations (Herrington et al. 1966; USAF TPS 1986; USN TPS 1977, 1997; Gallagher et al. 1992; Stoliker 1995; Olson 2003). More advanced details on system identification for aircraft are available from Klein and Morelli (2006), Tischler and Remple (2012), or Jategaonkar (2015).

Flight testing is a fascinating, exhilarating field of aerospace engineering. It's incredibly rewarding to connect theory with practice, and we hope that the thoughts we provide here will draw students into a deeper understanding of flight through the intertwined approaches of theory and flying in flight test. And we hope to inspire the next generation of flight test professionals (Figure 1.14) to pursue this fascinating line of work. Hang on for a wild ride!

Nomenclature

M_{MO}	maximum operating Mach number
V_{MO}	maximum operating limit speed
V_{NO}	maximum structural cruising speed

Acronyms and Abbreviations

AAF	Army Air Forces
CFR	Code of Federal Regulations
CG	center of gravity
DT&E	developmental test and evaluation
FAA	Federal Aviation Administration
HARV	high alpha research vehicle
LEX	leading-edge extension
NACA	National Advisory Committee for Aeronautics
NASA	National Aeronautics and Space Administration
OT&E	operational test and evaluation
PSP	pressure-sensitive paint
UAV	unmanned aerial vehicle

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