Kate M. Pavlock
National Aeronautics and Space Administration
Dryden Flight Research Center
P.O. Box 273
Edwards, California 93523-0273
661-276-3209

1. Flight Test Engineering

The year 1903 began what was known as the Aerial Age, marked by the flight of the Wright Flyer in Kitty Hawk, North Carolina. It was the first powered, heavier-than-air vehicle that sustained controlled flight with a pilot aboard. Only two years prior, the inventors, Orville and Wilbur Wright, frustrated with the results of their previous glider flight tests, decided to use modeling and wind-tunnel tests to develop an optimal airfoil design. Designing and building their own wind tunnels, the pair patiently studied and cataloged over two hundred self-manufactured airfoil models (Benson 2010). Later, after performing more detailed parametric studies on some of their more promising designs, Orville and Wilbur developed a propeller for their proven 1903 "flying machine". They used a variety of skills to design, verify, and flight test their ideas. Perhaps unknown to these leaders of aviation, their efforts set the stage for the discipline that would later be called "flight test engineering."

Flight test engineering uses science and mathematics to make aeronautical vehicles and systems effective, efficient, and more useful for mankind. From determining the effectiveness of military radar systems to researching techniques to reduce the sonic boom effects of supersonic aircraft, flight test engineering applies the natural laws of science to solve aeronautical and aerospace problems, creating systems that can do more and aircraft that can fly faster, higher, and farther than ever before.

The need for flight test means that the flight system or vehicle under test requires accurate assessment in the flight environment rather than relying on the results of ground-based verification methods such as wind tunnels, simulators, and software models. Ground-based methods, although useful, are limited in their ability

to fully model the dynamic and true nature of actual flight. These limitations are summarized below (Appleford 2005):

- adequate replication of actual flight conditions on the ground is often impractical, if not impossible;

- particular flight conditions may be insufficiently defined or too complex to be replicated or simulated;

- all but the simplest of aircraft incorporate many systems having complex interactions; those interactions may be more difficult to fully investigate on the ground;

- despite our best endeavors, significant discrepancies between actual flight behavior and ground-based predictions are common; flight test data are essential to both improve and validate the accuracy of models and simulations.

The scope and definition of flight test engineering varies among organizations; however, a common theme is threaded among each: flight test engineering is an interdisciplinary effort with the objective of testing an aircraft or system in its operational flight environment. Executing flight test techniques to acquire specific data during flight test can be considered the finale of the total flight test engineering effort. This chapter provides a top-level perspective of flight test engineering for the non-expert. Additional research and reading on this topic is encouraged to develop a deeper understanding of the specific considerations involved in each phase of flight test engineering as well as the differences that may exist between aeronautical organizations that engage in flight test engineering.

1.1 Types of Flight Test

The types of flight tests performed are often grouped by their purpose. Three common categories are experimental, development and certification, and production flight test. Experimental flight test involves verifying or refuting the validity of an aeronautic hypothesis; essentially exploring the unknown of aeronautic capabilities. One of the most iconic examples of experimental flight test involves United States Air Force pilot Captain Chuck Yeager and the Bell X-1 aircraft achieving supersonic flight on October 14, 1947 following years of research in high speed aerodynamics. After iterations of design concepts carried out by the National Advisory Committee for Aerodynamics (NACA), the predecessor to the National Aeronautics and Space

Administration (NASA), and the United States Army, the X-1 followed a "bullet with wings" configuration with the purpose of gathering aerodynamic data at high speeds (Anderson 2001). With the success of breaking the sound barrier, the X-1 became the first of a series of X-planes: American experimental aircraft used for testing new technologies and concepts.
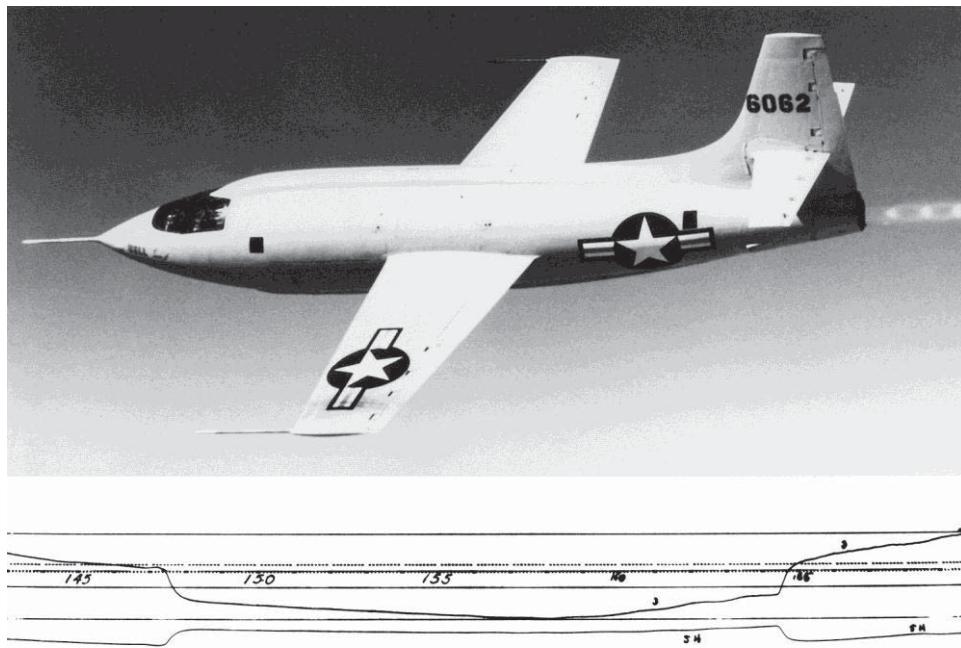

Fig 1: The Bell X-1 in flight with superimposed "Mach Jump" paper tape data record of the first supersonic flight.

Development and certification flight test involves demonstrating compliance with all requirements, ensuring that the aircraft or system does what it was designed to do. During developmental test, a representative aircraft or system is used to validate the entire fleet or system stock. When specifically dealing with the developmental test of aircraft, test pilots often perform specific maneuvers in flight commonly referred to as flight test techniques. A few common roles of developmental flight test are defined below:

- **Performance:** evaluation of performance abilities such as aircraft speed or range, or system communication or sensor accuracy.
- **Structural:** evaluation of aircraft or system loads to verify structural integrity.
- **Handling qualities:** aircraft's controllability and response to pilot inputs.

- **Flight envelope:** range of speeds and altitudes permitted for aircraft or system operation.

Production flight test deals with testing each production copy or system rather than testing a single asset to obtain acceptance of all. The goal of production flight test is to ensure individual aircraft are manufactured properly and is in a condition for safe operations. It is the final stage of the production process and is a prerequisite to each aircraft being issued a Certificate of Airworthiness and released to the customer. Production flight test does not demand the full range of test outlined in development and certification flight test. Instead, efforts such as performing operational checks, instrument inspections for proper placarding, and other assessments are made to ensure each aircraft meets its design specifications and that systems operate correctly. For example, in 2013 Boeing completed the first production flight test of the new 787-9: a longer version of their newly certified 787 Dreamliner. Testing included standard Boeing-defined production flight test requirements with the addition of criteria specifically aimed at evaluating the different propulsion and handling characteristics of the 787-9 (Norris 2013).

2. Flight Test Engineering Approach

With the foreknowledge and appreciation of what flight testing can provide, flight test engineering aims to provide solutions to aerospace needs. The concept and method of flight test engineering may differ between engineering organizations depending on their fundamental purpose. Some organizations may focus on performing research and development activities while others engage in more mature activities, such as integration and test. Nonetheless, the big-picture perspective of flight test engineering encompasses all of the engineering activities that are required to evaluate an aircraft or system in its intended operational flight environment, gather data, and report results. Top-level explanations of these activities are discussed in the sections below.

2.1   A Team Effort

Since the days of the Wright brothers, flight test engineering has evolved into a disciple that requires an interdisciplinary effort to be successful. Putting together the right disciplines for the job is best accomplished with a thorough understanding of the flight test objective(s). In other words, the purpose behind the flight test

must be known in order to determine the necessary skills and expertise to get there. Most traditional flight test engineering teams contain the following types of contributors: discipline or research engineers; integration engineers; fabrication engineers; quality assurance experts; system safety experts; pilots and flight test engineers; mechanical and instrumentation engineers; aircraft systems engineers; project managers; mechanics, and technicians. With such a dynamic group of specialized individuals, a well-organized and cohesive test team is crucial. Roles and responsibilities must be clearly defined to minimize confusion and duplication of effort as well as to ensure that all required tasks will be properly staffed and executed.

2.2   *Systems Engineering Approach*

The world-renowned theoretical physicist Albert Einstein has been quoted as saying, "If we knew what we were doing it would not be called research, would it?" (Prindle 2012). Like research, flight test engineering is not an exact science. However, tried-and-true approaches have been developed that are used to guide flight test engineering activity toward success. A common and proven approach to flight test engineering is the systems engineering approach. Systems engineering is an orderly build-up approach to the formulation, development, integration, and use of the components that form a system. The purpose of systems engineering is to ensure that the components and their subsystems work together effectively and efficiently, building-up to evaluating the functionality of the overall system. When applied to flight test engineering, it includes the build-up and verification of requirements, design, integration, and test. This dynamic approach requires continual forward planning that is adaptable to any new findings that may alter an initial plan. The following subsections of this chapter follow the traditional systems engineering approach to flight test engineering.

2.3   *Objectives and Requirements*

Defining objectives is the key to acquiring the necessary resources and identifying the flight test requirements that will be needed to achieve the objectives. In addition, objectives provide a metric for ensuring that the engineering tasks are aligned with the purpose of the flight test. Objectives must be clearly and concisely stated so that the team will be able to identify when an objective has been met.

Once objectives have been identified, the requirements needed to meet the objectives are developed. While simple in theory, requirements development often differs among each flight test effort. Several core principles, however, should be considered when developing requirements. Requirements should clearly identify:

- the needs of the end user and any stakeholder requirements;

- the functional system characteristics ("what must the system do?");

- the physical system characteristics ("what environmental constraints affect the design?");

- the performance characteristics ("how well must the system perform?");

Requirements must also be verifiable with acceptance criteria for qualitative and/or quantitative evaluation in order to prove the requirement has been met. Each requirement should be independent and traceable to an objective to ensure it remains purposeful. Requirements should be developed until an overview of the overall system and its associated subsystems is revealed which can provide a basis for the design, fabrication, integration, and test. Correctly defining the flight test objectives and requirements lays the foundation for the rest of the flight test engineering effort and is the starting point for design.

2.4   Design Phases

The ultimate goal of the design phase is develop all the necessary documentation, such as drawings, to facilitate the manufacture of the designed aircraft or system. The design process is iterative where the progress is often defined within three sequential phases based on design maturity: conceptual design, preliminary design, and detail design. During the conceptual design phase, engineers develop unrefined designs that satisfy top-level requirements. Knowledge of both current engineering practices as well as new creative approaches should be considered during this initial phase to develop an array of conceptual designs. For example, if an objective existed to develop a self-propelled supersonic aircraft, a conceptual design may start out by incorporating a previously-proven shape concept of a slender fuselage in order to minimize the amount of drag the propulsion system would be required to overcome. However, the exact mold and form of the fuselage may become a unique construction once the design is refined to meet the specifically defined requirements the designer is working to. The preliminary design phase is where the preferred conceptual

design is refined to best meet specified requirements. For instance, using the example of the supersonic aircraft, a specific aircraft performance requirement related to achieving a precise range or altitude capability may require further configuration changes to the conceptualized slender-body fuselage in order to make it more aerodynamic. Detailed modifications made in the preliminary phase are often achieved with the help of modeling and simulation tools that provide in-depth information beyond that provided by analytical theory. Modeling and simulation tools allow engineers to visualize a part or system and simulate its behavior under various environmental conditions. Some common design tools are described below:

- **Computational Fluid Dynamics (CFD):** CFD uses simulated fluid flow software algorithms to solve fluid flow uncertainties. Wind-tunnel and full-scale flight test data validate CFD software that can later be used for improved analysis during future design efforts.

- **Finite Element Modeling (FEM):** FEM is a computational tool often used for structural analysis to determine the effects of loads through the visualization of material stresses due to bending or twisting of a dynamic environment. In principle, FEM divides an unknown area into sections through a set of computational equations and then reconnects those equations back to the overall area to solve overall unknowns.

- **Wind Tunnels:** Wind tunnels utilize fans to simulate flight of the test article, a model of the preliminary design, to determine how the air interacts with it. The model is often instrumented to measure the forces generated by the airflow, such as pressure across its surface. If mounted on a force balance, lift, drag, lateral forces, yaw, roll, and pitch moments over a range of angle of attack can also be determined.

Preliminary design concludes with detailed drawings and schematics to be used in the detail design phase. The detail design phase incorporates the engineering data required to support manufacture, such as defining applicable number, size, and location of fasteners for assembly. If any unique or one-of-a-kind manufacturing tools are required to facilitate the fabrication or integration of the design, those are also designed during the detail design phase.

The completion of each design phase often incorporates a design review. Correcting erroneous designs can be costly to the engineering budget and schedule as well as impose unwanted risk if not identified early during design. Design reviews provide a technical assessment of whether the design requirements have or have not been met. Review participants should include all associated discipline engineers as well as experienced independent engineers to ensure design correctness and appropriateness. Effective collaboration is key to addressing design challenges successfully and in a timely matter. In addition to requirements verification, other considerations should be made at design reviews to ensure a well-vetted solution. Several examples are outlined below:

- Basing design concepts on similar and previously proven designs have the potential benefit of reducing time, effort, and cost. However, proceed with caution when revitalizing historical components. Care must be taken to ensure historical validation methods meet the environment of its repurposed use. At a minimum, re-validation efforts must be performed where deltas are identified.

- What are the best methods to test the design and can the appropriate test resources be acquired?

- Do the test resources have inherent limitations that could alter the quality of the test that is performed?

- Can the proposed design perform as required and survive the intended flight environment (e.g. temperature, pressure, vibration) during flight testing? Redesign may be necessary if components are not robust enough to survive the anticipated flight test environment. Environmental testing as well as potential redesign efforts should be considered in the schedule.

- What engineering controls can be designed into the system to mitigate risk? The most successful mitigations are those that can be incorporated into the system and the most cost effective time to do so is during the design phase.

- Does the design facilitate appropriate installation and maintenance? Difficulties encountered during installation and maintenance can create significant cost and schedule impacts.

- Have the appropriate human factors considerations been incorporated into the design? Does the design create an unnecessary increased workload to the operator or pilot that can be a distraction

during flight test? Are human interfaces readable, accessible, and easy to interact with in the flight environment?

2.5 Integration and Verification

Integration and verification are key activities that move requirements and designs into realized products. Successful integration efforts require thorough preparation. Time should be scheduled and spent ensuring all applicable fabrication and assembly drawings are complete, necessary machining and associated materials are available, and that technicians and engineers performing tasks, such as fabrication, machining, or software coding, are properly trained. The test team should also strongly consider incorporating aerospace standards into the integration strategy with respect to material use, processes, and practices. When procured assets are used, industry specifications should be consulted to help ensure acquired parts are suitable for the flight test environment. Multiple private sector and military aerospace standards and specifications are available for consideration that aid in the production of safe, quality, and useful products through the incorporation of best practices.

Integration planning decisions should culminate into a documented interface plan that establishes the internal and external interfaces of each stage of product development and integration. Interface development should be built from the bottom up as components turn into subsystems until the overarching system interface is defined. Functional and physical compatibility of each defined interface, whether internal or between systems, should be defined to ensure interoperability. Properly identifying interfaces also help in developing effective integration procedures.

Throughout the integration process, the team should verify progress is made in accordance with specified requirements and applicable standards and specifications. Verification ensures that each component and system functions properly when integrated. The tasks, conditions, and resources (such as test equipment, test range assets, personnel, et cetera) needed to perform verification must be identified along with associated acceptance criteria to determine the pass/fail characteristics of the chosen verification method. Verification is traditionally accomplished by any one or combination of the methods described below (Defense 2012):

- **Demonstration:** Demonstration is the practical display of the expected functionality and is often used when quantitative assurance is not required or possible.

- **Inspection:** Inspection is the examination of a product(s) compared to design documentation. Inspection may include visual verification of compliance via certifications or physical measurements to confirm conformance to specified physical, material, or component characteristics as well as workmanship standards. This method provides a qualitative rather than quantitative verification and is the primary means of assuring physical configuration compliance.

- **Test:** Testing is the principal means to assure functional compliance to requirements and is generally associated with data gathering under controlled and repeatable conditions. Testing is often used to establish the quantitative operational characteristics and limitations of a system. Some typical testing examples are:

  - *Simulator:* Pilot-in-the-loop simulators typically include a cockpit emulator with external views and pilot control interfaces and displays. Simulation is validated against predicted models and updated using flight data to assure fidelity. One use of simulators is to enable pilots to easily test dynamic aspects of flight test such as the feasibility of test maneuvers given defined test point criteria.

Fig.2: C-17 Globemaster Flight Simulator

- *Environmental testing:* Environmental testing is aimed at verifying that the physical integrity of an item under test will survive the intended flight environment. Temperature and pressure chambers along with vibration tables are used to imitate some characteristics of the anticipated flight environment.

- *Avionics bench testing:* Bench testing couples hardware and software to replicate aircraft or research avionics systems to verify avionics software meets functional requirements and is free from system problems prior to integration into the flight vehicle.

- *Structural loads tests*: Loads testing determine the stress, strength, and fatigue the structural components can handle.

- *Engine test stands:* Facilities used to characterize engine functionality and performance, to include airflow and distortion effects and thrust, during different operating scenarios.

- *Ground vibration tests:* Used to determine the structural mode characteristics of the aircraft, to include natural frequencies, mode shapes, and damping tendencies.

Fig.3: Instrumented wing of the Active Aeroelastic Wing F/A-18 test aircraft connected to electro-mechanical shaker device in preparation for ground vibration tests.

- **Analysis:** Use of analytic techniques to assess system performance.
    - *Computational fluid dynamics*: CFD uses simulated fluid flow software algorithms to solve fluid flow uncertainties.
    - *Simulations*: Enable subsystems and systems to be modeled and integrated with simulated flight conditions to support analyses such as a sensitivity analysis of control surface configurations and test nominal and extremes before placing a flight asset or pilot into a potentially dangerous environment.
    - *Software verification*: Verifying that software meets all functional requirements and performs correctly.
    - Stress analysis: Provides quantitative description of the stress over all of the parts of the system that are under evaluation, and any subsequent deformation resulting from those stresses.

Verification follows each level of integration to ensure that the system satisfies specified requirements. When requirements cannot be verified, users and stakeholders should be notified and discussions should take place to determine whether it is feasible to redefine the requirements in order to meet the objective, rework the scope of effort, or brief and accept the associated risks with the current state of design and analysis. When requirements are verified and confidence in the functionality of the system is gained, flight test constraints, hazards, and risk mitigations can be refined.

After component, subsystem, and system verification has been accomplished, end-to-end testing should be performed. End-to-end testing exercises all elements through all operational scenarios with respect to how the system as a whole interacts to ensure that the data flows correctly and the system functions as required throughout the entire operational environment. Operational scenarios should be developed that will exercise all modes and phases of the system, including startup, shutdown and a run-through of any known contingency scenarios, to fully evaluate and develop a thorough understanding of the operational aspects of the system prior to the actual flight test (Unknown 2007).

3. Configuration Management and System Safety

As stated in the chapter introduction, flight test engineering is comprised of various engineering disciplines performing interdisciplinary activities. This means that the work of one may affect or contribute to the work of another. Working in such an interdependent and diverse environment creates both challenges and benefits to flight test engineering. For instance, a challenge of this interdependence is the development and management of clear and effective communication. A benefit, however, is improved evaluation and assessments due to a diverse set of perspectives. The following sections describe two topics related to the challenge of communication and benefit of improved assessment: configuration management and system safety.

3.1   Configuration Management

Configuration management is the systematic and formal control of the authorization, design, workmanship, and performance of assets that are under development. The goal of configuration management is to ensure that the configuration of systems and components are well understood at all times. Configuration items are items which, if their configuration is not properly managed, have the ability to affect another component's or the system's ability to fulfill a requirement. Configuration items should be identified early during the design phase. Mismanaged and ill-communicated configurations have unfortunate and costly effects and can critically compromise safety. Changes should not be implemented without a thorough understanding of the effects of the change on the overall system or vehicle. These important points are highlighted by the lessons learned of the X-31 program. The X-31 program was designed to test thrust vectoring technology on fighter aircraft for improved maneuverability. Significantly, the aircraft's flight control system could provide controlled flight at high angles of attack where traditional fighters were prone to stall. The flight control computers of the X-31 relied on air data from the nose boom to make accurate flight control commands. In January of 1995, after 289 successful sorties, the pilot of the X-31 ejected and the aircraft crashed north of Edwards Air Force Base in California. Mishap investigation reports state that erroneous air data caused excessive compensating control gains, that resulted in the aircraft becoming unstable (Merlin, Bendrick, and Holland). One of the contributing factors of the mishap was that the air data probe provided erroneous information due to partial icing in flight. Earlier in the program after a multitude of flight test sorties, the

probe had been changed to one that provided more accurate air data measurements. The configuration change

had been formally approved within the project; however, the project members were unaware that the probe was

prone to icing. Furthermore, the fact that probe de-icing was inoperable was poorly communicated to new

project personnel and pilots who were on the project during the mishap some 150 successful flights after the

configuration change. To add insult to injury, the pitot heat switch (probe de-icing switch) in the cockpit was

not labeled "inoperable" (Merlin, Bendrick, and Holland). This configuration change resulted in misplaced

trust in the functionality of the air data probe by the engineers and pilot. Although there were additional

contributing factors to the X-31 mishap, it continues to serve as a significant reminder of the importance of

proper and well-vetted configuration control to ensure mission success and most importantly, safety of flight.

Fig.4: The X-31 aircraft orientated nearly perpendicular to the flight path using thrust vectoring technology.

As noted in the X-31 example, interdisciplinary review and approval before a change is implemented is

essential in buying down the effects and risk that may be associated with a change. All configuration change

requests should be discussed prior to work start and should include approval of all necessary disciplines to ensure interoperability between systems. When configuration management is effectively implemented throughout the lifecycle of a project, functional and physical components will be well understood at all times. A crucial aspect of configuration management is maintaining airworthiness. An airworthy aircraft meets the conditions of its type design and is safe for operation. Any modification from the originally certified configuration of an aircraft, whether physical or functional, must undergo an effective hazard mitigation process until risk has been eliminated or an acceptable level has been achieved to ensure the aircraft is safe to fly after the desired modifications are made. A discrepancy can be defined as a difference between the expected and actual results, behavior, or physical requirements. When a discrepancy is identified, timely documentation, discussion, and corrective action are critical to maintaining airworthiness and ensuring mission success. Each discrepancy should be assigned a measure of criticality in order to identify those that may affect the safety or the success of the flight test effort. This method will be helpful when programmatic decisions and tradeoffs are being made.

3.2   *System Safety*

Flight test is inherently hazardous. Zero-percent risk can only be achieved by not flying. However, without flight test, aeronautical and astronautical discovery would grind to a halt. Therefore, risk must be managed. Risk management can be achieved in part through a system safety analysis which should be updated throughout all stages of the flight test engineering effort. Effective system safety analysis includes the identification, evaluation, risk mitigation response, and tracking of risks associated with the flight test engineering effort. The goal is to ensure that the potential for injury to personnel or damage to assets is identified and either eliminated or minimized to an acceptable level.

Subject matter experts, to include discipline engineers, mechanics, and pilots should be included in system safety analysis discussions to ensure a well-vetted evaluation of potential hazards and mitigations. The effort should begin early and be revisited as system design, development, and test evolves or changes scope. This approach provides an opportunity to incorporate mitigations such as mechanical, electrical, or software

engineering controls into the system or test process, thereby reducing the impact of human error. For example, electrical fail-safes such as circuit breaker protection can be designed into the system to protect against current exceeding the capacity of the wiring protecting against potential fires. Other mitigations such as warning and caution placards within documented procedures or on test equipment also help to bring attention to hazards and minimize human error. The X-31 example described earlier further promotes the importance of thorough analysis and proper mitigations. For instance, mishap investigators noted that the team did not fully evaluate potential implications of not having the same de-icing capability as the original probe (Merlin, Bendrick, and Holland). In addition, the pitot-heat switch in the cockpit should have been placarded as "inoperable" to facilitate pilot situational awareness.

Specific system safety analysis methods help to identify a potential hazard along with the initiating event and its associated effects. With this information define, it becomes easier to determine appropriate corrective measures and controls that have the potential to eliminate or limit the effect(s) of the hazard. If a hazard cannot be eliminated, consideration should be made to determine how the hazard can be minimized or controlled. Several hazard analysis techniques and methods have been developed over the years to identify and mitigate hazards. These techniques are well-known within the flight test engineering community and provide a good starting point for any system safety analysis:

- **Event sequence diagrams:** Models that describe the sequence of expected events as well as responses to off-nominal conditions.
- **Failure Modes and Effects Analyses (FMEAs)**: Bottom-up evaluations of potential component failures and their effect on the overall system or process.
- **Qualitative top-down logic models:** Evaluations of how combined individual component or system failures can develop into additional hazards.
- **Human reliability analysis**: A method to understand the likeliness and association of human failures to system failures.

4. Flight Test

The flight test phase requires the same thorough build-up approach as the preceding engineering phases and consists of these core stages: planning, executing the mission, and data analysis and reporting.

4.1   Flight Test Planning

Flight test planning consists of the organization and allocation of resources toward the development of a flight test approach that will validate each flight test objective. A significant part of flight test planning is related to developing good test methodology, which is how the test will be conducted to achieve each objective. This requires thorough coordination and discussion with all required technical disciplines associated with the test in an effort to promote test efficiency and success. The elected methodology is documented in a flight test plan. A flight test plan is a documented systematic approach to execute the mission and includes, at a minimum, the following topics:

- purpose and scope of the test;

- number of flights needed to accomplish each objective;

- duration of each flight;

- flight path;

- required flight maneuvers and test point acceptance criteria;

- test configurations;

- test conditions;

- risk reduction techniques;

- data collection, including measurements, data rate, and format type;

- data-gathering and reduction methods to evaluate test results during and/or post-flight.

Determining appropriate flight maneuvers, test point conditions, and test point acceptance criteria are among the most critical success-driven factors of flight test with respect to obtaining the data needed to validate the objective(s). Flight test maneuvers are often dictated by the focus of the mission. Two traditional focuses of

flight test include the determination of vehicle performance and handling qualities. In general, the role of performance testing is to quantify the capabilities of an aircraft with respect to performance, such as speed, range, drag, et cetera. Since performance characteristics are intrinsically tied to thrust and power, aircraft conducting vehicle performance flight tests often incorporate instrumentation related to engine revolutions-per-minute (RPM), fuel flow, engine pressure ratio (EPR), total fuel, along with aircraft altitude and airdata (temperature and pressure). Some examples of performance tests include climb and descent rate performance, take-off and landing (measuring time, distance, and airspeed to rotation), and cruise (Vleghert 2005). Handling qualities testing, on the other hand, evaluates the aircraft response to a disturbance or flight control input throughout the range of flight to determine stability and control characteristics of an aircraft. It involves the "flyability" of an aircraft based on its inherent characteristics and the pilot's input techniques combined. Therefore, handling qualities flight test requires a heavily instrumented aircraft and data recording of flight control positions and forces, linear accelerations, airspeed, altitude, angle of attack, and sideslip to name a few (Lee 2005). Testing occurs in a build-up fashion to establish a safe handling qualities flight envelope. For example, initial handling qualities test maneuvers start in the middle of the predicted flight envelope and build up toward the extremes of each corner. Handling qualities flight test maneuvers incorporate open-loop flight test techniques to excite an aircraft mode of motion. For instance, a pilot may execute an abrupt rudder command onto one rudder, called a singlet, to excite a lateral directional mode and evaluate the frequency response of the aircraft. Or, the pilot may execute a doublet, symmetric input in both directions (left then right rudders), for further evaluation of aircraft response. For pilot-in-the-loop tasks, such as air-to-air-tracking and formation flight, a Cooper-Harper rating scale is often used as an aid of quantifying pilot judgment. The scale is a decision tree guide to rate a task with regards to the demands placed on the pilot to perform it.

Handling Qualities Rating Scale

Adequacy for Selected Task or Required Operation	Aircraft Characteristics	Demands on the Pilot in Selected Task or Required Operation*	Pilot Rating
	Excellent Highly desirable	Pilot compensation not a factor for desired performance	1
	Good Negligible deficiencies	Pilot compensation not a factor for desired performance	2
	Fair - Some mildly unpleasant deficiencies	Minimal pilot compensation required for desired performance	3
Is it satisfactory without improvement? — No → Deficiencies warrant improvement	Minor but annoying deficiencies	Desired performance requires moderate pilot compensation	4
	Moderately objectionable deficiencies	Adequate performance requires considerable pilot compensation	5
	Very objectionable but tolerable deficiencies	Adequate performance requires extensive pilot compensation	6
Is adequate performance attainable with a tolerable pilot workload? — No → Deficiencies warrant improvement	Major deficiencies	Adequate performance not attainable with maximum tolerable pilot compensation	7
	Major deficiencies	Considerable pilot compensation is required for control	8
	Major deficiencies	Intense pilot compensation is required to retain control	9
Is it controllable? — No → Improvement mandatory	Major deficiencies	Control will be lost during some portion of required operation	10

Pilot decisions

* Definition of required operation involves designation of flight phase and/or subphases with accompanying conditions.
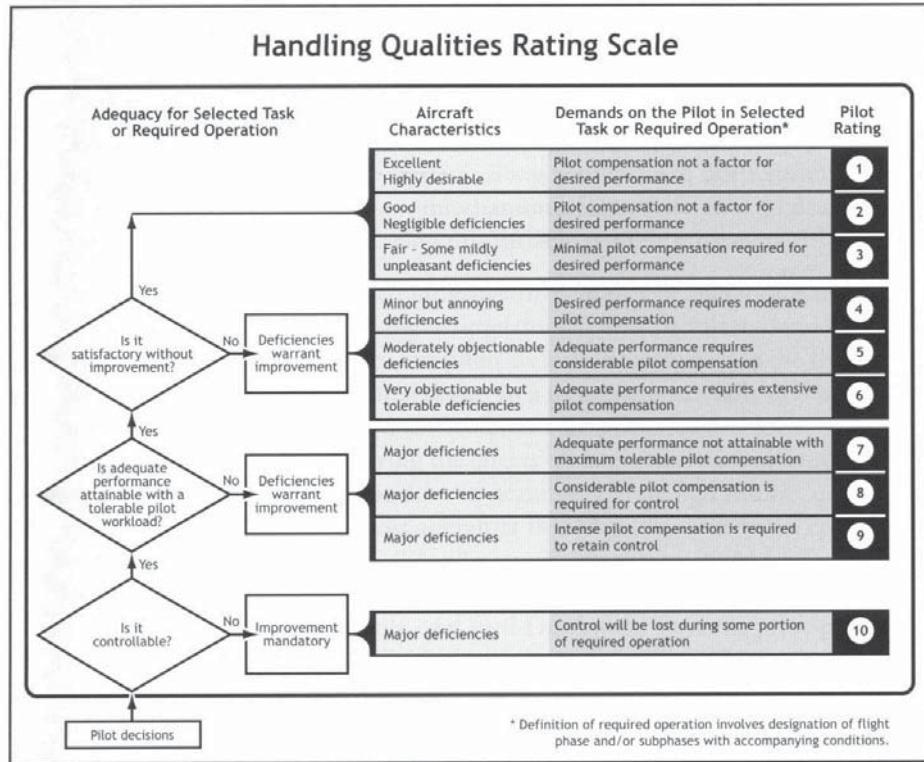
Fig.5: Cooper-Harper rating scale for evaluating aircraft handling qualities.

Although not discussed here, additional flight test focuses include the evaluation of aero-elastic stability (flutter) and determining structural loads in flight, among others. There are numerous sources of additional information available that provide detailed explanation of these flight test focuses, as well as others not mentioned here. Since only a brief introduction has been provided on this topic, additional investigation and research should be performed to better understand the objectives, associated flight test techniques, and maneuvers associated with each test focus type.

Test point conditions describe the prerequisites for starting each test point. Some test point conditions may include aircraft control surface configuration, gear configuration, aircraft attitude, weather constraints, airspeed, and aerodynamic loading. Identifying the proper conditions will improve test efficiency and ensure the proper data is collected. However, it is also important to determine the limits that a test must be executed within to produce accurate data. These limits, often termed acceptance criteria, help engineers and pilots decide whether a test point was successfully completed or needs to be repeated. For example, if a test point is

defined to collect straight-and-level air data information at an altitude of 40,000 feet mean sea level (MSL) at a speed of 200 knots indicated airspeed (KIAS), are the data considered acceptable if the pilot is flying at an altitude of 39,900 feet MSL or at a speed of 198 KIAS? Such considerations should not be an afterthought to avoid expensive repetitive testing. Thorough up-front planning, such as pre-determining acceptable tolerances in the example above, will reduce the risk of wasting a test or causing inefficiency while conducting the test. The planning considerations mentioned above typically culminate into a formally documented flight test plan. A flight test plan should outline the most effective, efficient, and safe way to validate the objective(s). The initial draft of a test plan should be the best information known at the time of development; however, flexibility is the key to success. Modifications may be needed as knowledge is accrued through actual flight experience. Changes may need to be made as responses in the flight environment prove better or worse than expected. Changes may include removing, adding, repeating, or altering the scope of test points. All modifications should follow a predetermined process for identifying, discussing, documenting, and approving changes in order to ensure that any implications associated with the change will not adversely affect the safety or success of the test.

4.2   Executing the Mission

Although each mission may incorporate a subset of tests defined in the overarching flight test plan, a further and more detailed mission plan should be developed and communicated to the test team for each flight. The mission details are often documented in a set of flight test cards rather than a flight test plan. Flight test cards outline a specific sequence of events in a logical, efficient, and safe manner in which to conduct the test. Key attributes of a flight test card include:

- identification of test aircraft;
- test card revision and card numbers;
- test objective;
- aircraft and test point configuration description; and
- test maneuvers and test point acceptance criteria.

Despite the amount of information documented in the flight test card set, each card should be kept clear, concise, and understandable so as not to cause confusion during the mission. The individuals conducting the test should, while using the test cards, be able to direct the progression of the mission and ensure that all associated test team members are on the same page each step of the way.

Aircraft: GIII – 804	Serial No: 344	Flight No:	Date:	Revision: 03	Card No. 19
Event: PHASE 0A					

TEST: 10K CHECKS, 0.6M

GEAR	FLAPS	Airspeed (KCAS)	MACH	Altitude (HP)
UP	0	333 ± 5KTS	0.6 ±0.02	10K ±500 FT

TP	DESCRIPTION	
1	STEADY STATE (WINGS LEVEL)	1 MIN

LOADS CAUTION
Rudder Limit during Doublets & 2-1-1
−2 < x < +2 deg

TP	DESCRIPTION	
2	DOUBLETS	
	PITCH (3X)	ALT FWD/AFT INPUTS
	ROLL (1X)	
	YAW (1X)	
	YAW-ROLL (3X)	ALT L/R INPUTS
3	2-1-1	
	PITCH (3X)	ALT FWD/AFT INPUTS
	ROLL (1X)	
	YAW (1X)	
	YAW-ROLL (3X)	ALT L/R INPUTS
4	BANK-TO-BANK	
	30R -> 30L	¼ YOKE
	30L -> 30R	¼ YOKE
	30R -> 30L	¾ YOKE
	30L -> 30R	¾ YOKE
	30R -> 30L	FULL YOKE
	30L -> 30R	FULL YOKE
5	ANGLE CAPTURES	PILOT COMMENTS/ OVERSHOOTS
	PITCH	± 5 DEG
	BANK	± 15-30 DEG
	HEADING	± 30 DEG
6	FUEL CHECK	L:_____ R:_____ T:_____

Fig.6: Sample flight test card.

Review of the final approved test cards should occur at a pre-mission brief. A pre-mission brief is a coordination meeting at which all test participants review the mission objective, scope, procedure, and requirements in an effort to ensure that everyone executes the same test with the same expectations of roles,

responsibilities, and outcomes. Explicit discussion should take place regarding specific test point maneuvers, all relevant hazards, and mishap contingency procedures. If significant test planning errors are discovered during the pre-mission brief, careful consideration should be made to determine whether to continue or postpone tests. Minor test sequence changes may be penciled in; however, major changes should warrant a delay in the mission to allow time for a proper and comprehensive assessment to be made by all technical disciplines to ensure the change does not adversely affect the safety or success of the mission.

Most flight tests are executed with the support of a test team in a ground-based control room in which displays and cameras provide the data required to monitor the safety and success of the test. The test team typically consists of the test pilot in the test aircraft, a safety chase aircraft with a pilot monitoring the flight in close yet safe proximity to the test aircraft, and a test conductor with associated technical discipline personnel in the control room. All test team members must be intimately familiar with the system and with the parameters driving the success and safety of the test. Situational awareness is essential to an inclusive perception of both the potential impacts of test trends and such uncontrollable factors as weather or other aircraft in the test area. Communication must be carefully defined and documented prior to test and effectively followed during the mission to ensure that all information is transmitted. The best decisions can be made only if the best information is available to everyone involved.

Fig.7: Example of a mission control room.

Mission debriefs are another important aspect of flight test execution. Debriefs are a time to evaluate accomplishments and document anomalies regarding each mission. Conducting a thorough discussion reviewing what went well, areas of improvement, unexpected responses, and verification of test point completion pays dividends toward ensuring ongoing efficient, safe, and successful flight testing. As with the pre-mission brief, a card-by-card review of the test cards must be performed to facilitate the detailed discussion among all of the test team members who were associated with each test action that was performed. Mission debriefs may provide the first indication of the need to perform further data analysis to ensure that anomalies are not present if they were not obviously determined in real-time during the test. Although sometimes a difficult decision to make, it is crucial for the test team to decide to delay further testing when unacceptable or unexplainable results occur. Proper test planning will have anticipated the need for down-time in the schedule to accommodate detailed data verification. The decision to proceed with flight testing should be made based on both technical and risk management with safety being paramount.

4.3   Data Analysis and Reporting

The primary product of flight testing is a set of flight test data. Data requirements are dictated by the flight test objectives and determined well in advance of the actual flight test. A detailed understanding of the tests, required measured parameters, data sampling rates, accuracy, quality, bandwidth, and available data reduction methods is needed to determine the data requirements. Gathered data needs to be converted into a format that supports data analysis and reporting. This effort is called data processing and includes efforts such as converting binary data into Engineering Units, creating graphical representation of the flight test regime, converting time or space domain into the frequency domain, and signal filtering in an effort to remove interfering signals.

Once data processing is complete, the data are sent to discipline-specific analysts for data analysis. Data analysis is the act of looking at data and comparing it to predictions in order to draw conclusions. Data analysis is used to determine whether additional flights are necessary, verify that the current approach is both safe and is providing meaningful data toward matching predicted test results. When predictions and results do

not match, an update to the prediction tools, such as the models used during the design phase, should be considered to assure accuracy of future predictions. However, in scenarios where a redesign is deemed necessary in order to gain meaningful or accurate data, model updates are essential to the success of the redesign.

In addition to conducting data analysis, a summary of the mission and any critical information regarding the test should be documented in a flight report. Flight reports provide a historical record of what occurred, which allows for future reference to the test results, techniques, and procedures. Another important reason to report the results of flight testing is so that others may learn from mistakes made as well as build upon successes. Report content should be thorough and concise, clearly presenting an understandable yet not overwhelming amount of detail. The intent is to present findings such that someone executing the same test under similar conditions would obtain the same, or very similar, results outlined in the flight report. It is not surprising that the number of flight test accidents has fallen dramatically over the years; this is likely partly due to the flight test community sharing ideas and lessons learned.

5.0   Concluding Remarks

This chapter provided a top-level perspective of flight test engineering for the non-expert. Additional research and reading on the topic is encouraged to develop a deeper understanding of the specific considerations involved in each phase of flight test engineering. Although the scope of flight test engineering efforts may vary among organizations, all point to a common theme: it is an interdisciplinary effort with the objective of testing an aircraft or system in its operational flight environment. Thorough planning, in which design, integration, and test efforts are clearly aligned with the flight test objective, is the key to flight test engineering success. However, flexibility, effective communication, proper configuration management, and a comprehensive system safety analysis are equally essential, especially when changes to the original plan are warranted. When these and other flight test engineering best practices are followed, the benefit of contributing to and advancing the aerospace industry can be realized.

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