Effects of Stores Carriage on Aircraft Performance and Flying Qualities

Joseph Nichols
Air Force Test Center
Edwards Air Force Base, CA 93524
UNITED STATES

joseph.nichols.13@us.af.mil

ABSTRACT

Any time a new store configuration is added to an aircraft, modeling and simulation, ground testing and flight testing are required to verify that both aircraft and store are compatible with each other in the operational flight environment. This is accomplished through ground and flight testing to evaluate changes to aircraft performance, flying qualities, and structural loads when flying with the new store configuration. Testing to evaluate the ability of the store to survive the operational flight environment is also conducted. This lecture note describes standard approaches to determine aircraft performance and flying qualities for new store configurations.

1.0 INTRODUCTION

To begin, consider the question of what is a "store?" The answer is, a store is any device carried internally or externally on an aircraft whether it is, or is not, intended for separation in flight. This can include missiles, bombs, mines, torpedoes, self-protection systems, fuel tanks, dispensers, towed targets/decoys, or cargo drop containers. Depending on how the basic structure of the aircraft is defined, the store may also include the pylons and racks that attach the store to the aircraft. Stores are common on fighter aircraft and can also found on cargo-transport class aircraft that are used to air drop cargo, launch surface-to-air missiles or even launch small satellites into orbit. Store certification is determining aircraft-store compatibility and the formal publication of all the information necessary for the carriage and release of a specified aircraft/store configuration in the applicable technical and flight manuals.

Safe carriage and release testing of aircraft stores requires expertise in a number of engineering and test disciplines including, aircraft performance, flying qualities, structures and loads, vibration, flutter, electromagnetic environmental effects and aircraft separation. An emerging concern for stores testing is cybersecurity and the vulnerabilities that aircraft may be exposed to when connecting a store with the aircraft electronics. This paper will cover ground testing; aircraft performance, flying qualities, and loads which determine the effect of the store on the aircraft flight characteristics and structure; and captive flight profiles which address the effects of the flight environment on the store. However, limit cycle oscillation, or flutter, will be addressed in a separate paper.

Certifying a new store or store combination is among the most tailored of all flight test activities. It involves modeling and simulation, wind tunnel testing, certification by analogy, and flight test campaigns that can run from a single flight to dozens of flights. The concepts explained in this lecture note are focused on fighter aircraft, but the test techniques can also be applied to large aircraft that are fitted for external stores or drop internally carried stores.

There are several excellent references for flight testers to use in developing a store certification program. The first is a NATO Science and Technology Office AGARDograph, *Introduction to Flight Test Engineering* [1] which covers many of the flight test maneuvers that are common to aircraft performance and flying qualities with or without external stores. The next important reference is also a NATO AGARDograph, *Aircraft/Stores Compatibility, Integration and Separation Testing* [2] which includes additional reference material on the more specific topic of stores separation. Two United States references on testing aircraft with external stores are MIL-HDBK-1763, *Aircraft Stores Compatibility: Systems Engineering Data Requirements and Test Procedures* [3], and MIL-HDBK-244A, *Guide to Aircraft/Stores Compatibility* [4].

This educational note is broken into three main sections, 1) ground tests, 2) aircraft performance, flying qualities, and loads, and 3) captive flight profiles to verify store compatibility with the intended flight environment.

2.0 GROUND TESTING

There are three essential ground tests that should always be considered in any stores certification effort. It is important to determine the mass properties of the store, conduct a physical fit check, and test for electromagnetic environmental effects (E^3) [5]. MIL-HDBK-1763 [3] lists other ground tests that could be performed depending on the needs of the program. These include: vibration testing, structural integrity tests, carrier suitability testing, thermal testing, gun firing, and missile firing tests.

2.1 Mass Properties

The mass and inertial properties of the store are measured to verify that the test store is representative of the operational store and to verify that the modeling and wind tunnel work is applicable to the store being flight tested. Store weight and center of gravity are usually determined by using a mass balance like the one shown in Figure 2-1. The mass properties examination should determine the store dimensions, weight, center of gravity, and inertial properties. When a new variant of an existing store is considered, movement of the center-of-gravity by more than ½ inch, weight changes by more than five percent, or changes in inertial properties of more than 10 percent require a new mass properties evaluation.

Figure 2-1: Mass properties measurement [6].

When considering a new store, comparing the mass properties against an existing, approved store can sometimes reduce the amount of testing required through analogy.

2.2 Fit and Function Check

Before attaching the store to the aircraft the results of the mass properties analysis should be used to analyze the attachment mechanism and the clearances with the aircraft and other stores. Often computerized aircraft models are used to predict the store fit with the aircraft. A proper fit and function test is a prerequisite for flight testing. The fit check will determine adequate clearances, functional compatibility, and lanyard rigging as well as verify loading procedures and ensure that store movement will not result in impact with the aircraft or other stores. Functional compatibility should also be checked to determine that the store communicates properly with the aircraft across any data busses, that information from the store is properly displayed to the aircrew, and that aircraft and weapon software is compatible. Note the very tight clearance shown in Figure 2-2. A fit check will normally include a static ejection as well. The static ejection test, usually called a pit test, can be conducted from a rigid test fixture, iron bird, or from the aircraft itself. Neither test will be an adequate representation of the actual loads experienced in flight, but can be useful in building up to flight test and verifying that the hardware works properly.

Figure 2-2: Extremely Tight Fit Check [7].

2.3 Electromagnetic Environmental Effects (E^3)

Electrical components, even those that are not designed to radiate energy, can emit signals that interfere with other components and cause them to act in unpredictable ways. Examples of E^3 include electromagnetic interference, hazards to ordnance, hazards to personnel, and hazards to fuel to name a few. When munitions are involved this can create a dangerous environment. A particularly devastating example was an incident that occurred on the USS Forrestal in 1967. An F-4B was starting engines on the deck of the crowded aircraft carrier and, without warning, a MK-32 “Zuni” rocket was launched, probably due to a power surge when switching from external to internal power. The rocket hit the fuel tank of an A-4E on the other side of the deck, causing it to leak fuel onto the deck of the ship. The resulting fire caused many aircraft to burn and bombs to explode (see Figure 2-3). One hundred thirty-four sailors were killed and 161 more were injured by the fire and explosions. Twenty aircraft were destroyed and the incident caused approximately $72 million in damages to the ship [8].

Figure 2-3: 1967 USS Forrestal Fire [9].

The most general E^3 test is the electromagnetic compatibility (EMC) test. The EMC test shows the ability of an item to operate in its intended electromagnetic environment without causing or suffering unacceptable degradation due to electromagnetic interference. Electromagnetic interference (EMI) is any electromagnetic phenomena causing an undesirable response, ranging from a nuisance to complete degradation of mission performance. An EMI/EMC check should always be accomplished before flight with a new store.

The EMC testing should determine if any emitters on the store effect aircraft systems like radios, flight controls, navigation systems, sensors, and warning and caution systems. The store should also be checked to the extent possible for EMI effects from the aircraft. Sometimes the number of combinations of aircraft and store systems that must be turned on simultaneously can sum up to hundreds of combinations requiring many hours of testing. The use of statistical methods like design of experiments can be used to reduce the number of combinations that must be tested to identify compatibility issues. The EMI/EMC tests are often conducted on the aircraft parking ramp and in an open environment. Where possible, more precise cause and effect testing can be performed in an anechoic chamber as shown in Figure 2-4.

Figure 2-4: F-16 Aircraft preparing for testing in an anechoic chamber [10].

3.0 AIRCRAFT PERFORMANCE, FLYING QUALITIES, AND LOADS

Flight testing is required to verify that the store does not create unacceptable hazards or loads on the aircraft and also that the effects of the operational flight environment do not break the store. Performance, flying qualities (FQ), and loads testing verify that the aircraft can take the effects of the store or store combination. These tests require an instrumented aircraft and often a ground control room. Exact maneuvers and quantitative data are gathered to ensure that changes to performance or aircraft stability can be quantified. Effects on the store are gathered during this testing, but are further put to the test during operationally representative flight maneuvers and a speed soak run at high speed and low altitude in a captive flight profile test that will be described in Section 4.0. Sometimes all of this testing is combined into a single sortie. Both MIL-HDBK-1763, Appendix B [3] and MIL-HDBK-1797A [11] describe flight test procedures for stores compatibility testing that may be performed depending on the needs of the program. This section covers the most common procedures.

3.1 Aircraft Performance

Aircraft performance is often affected by the increased drag created by the addition of stores. Both aerodynamic drag caused by external stores, and induced drag from the increased weight will effect aircraft performance. For fighter aircraft, takeoff and landing performance, cruise performance, and maximum g-loading are often limited by the store configuration. It is important for stores that significantly increase the weight of the aircraft to test changes to takeoff decision speed, rotation speed, and initial climb out speed.

Landing tests are required to determine the ability of the aircraft to clear a barrier at the end of the runway and execute a full stop landing. Landing with stores can be an issue. Flight manual restrictions may be necessary to limit vertical velocity due to gear loads with stores, cross wind landings limits due to changed directional stability ($C_{n\beta}$) and runway limits due to tire dynamics and braking.

Cruise testing will determine changes to the range and endurance of the aircraft. Turn performance and maximum g-loading are often restricted based on engineering analysis of the loads on the aircraft structure. Wind-up turns are executed to ensure that the loaded aircraft can safely execute combat maneuvers within the predicted operational envelope. Descriptions of standard flight test techniques to determine aircraft performance can be found in the NATO Science and Technology Office AGARDograph, *Introduction to Flight Test Engineering* [1].

An alternate method for determining changes to aircraft performance while carrying stores is the drop technique [3]. This involves releasing a store from an instrumented aircraft in level flight and measuring the aircraft longitudinal acceleration. In this way changes in overall drag can be determined. This method is costly and not commonly used, but it can provide accurate measurements of overall aircraft performance.

The performance impact of a store is sometimes evaluated based on changes to the drag coefficient of the aircraft with stores loaded. Drag coefficients are typically very small and therefore for ease in usage, drag coefficient are converted to a drag count by multiplying the drag coefficient by 10,000. This results in drag count numbers on the order of 100 that can be used to compare different stores configurations and their effect on aircraft performance.

3.2 Flying Qualities and Aircraft Loads

Flying qualities (FQ), also called stability and control (S&C), testing is conducted for critical aircraft/store configurations as determined from analysis and build-up flight testing. The static stability in all three axes should be evaluated: pitch ($C_{m\alpha}$), roll ($C_{l\beta}$), and yaw ($C_{n\beta}$). Dynamic stability should also be evaluated for at least short period and Dutch roll modes. Each of these stability factors can be influenced by the size, weight and location of the store on the aircraft. The tests should be performed using an instrumented aircraft to obtain quantitative flying qualities data.

Loads tests are performed to determine the effect of stores carriage on aircraft structures. Loads testing is guided by wind tunnel results, modeling and by analyzing similar previously cleared stores. Test aircraft should be instrumented and a control room may be required for loads testing. Actual loads should be compared with predicted loads between each set of test points and when results differ significantly from predictions, testing should cease until the reasons for the differences can be determined. The FQ and loads tests are not designed to induce aircraft flutter or store oscillation, but if these phenomena are observed, testing should be immediately halted for evaluation before proceeding further.

Combined FQ and loads testing is the most efficient way to conduct a flight test program. However, FQ points should be performed before loads points. Test points build from benign conditions to the worst case conditions by building up in dynamic pressure (q), normal load factor (g) and lateral asymmetry.

A symmetric flight load as shown in Figure 3-1, can quickly become asymmetric when one store is released and the opposite store remains on the wing. This is often the most critical flight condition for a given store. Asymmetric loads can cause issues beyond just aerodynamics. Due to the mass properties imbalance on the aircraft, the principle vs body axes are even more askew causing kinematic coupling. The aircraft will always want to roll about the principle axes and not the body axes, and the farther the axes are askew the bigger the issue for coupling. Testing should be accomplished above 10,000 ft. AGL in the landing configuration to ensure that that no more than 75 percent of the stick and rudder control authority is required to safely control the aircraft with a store asymmetry. Cross winds must also be considered and where able, the aircraft should land with the cross wind coming from the loaded side of the aircraft. Other test maneuver considerations for asymmetric loads are noted below for FQ and loads flight test techniques.

Figure 3-1: Eurofighter loaded with Paveway IV bombs [12].

Aerial refueling may be required to complete the profile. If the test aircraft must land for refueling before the profile is complete, the stores should not be removed from the aircraft between flights. Prior to takeoff, screw and bolt-head positions on external panels, as well as internal flight control structures, should be marked to detect movement during flight. Following the completion of FQ and loads testing, the stores must be carefully examined to look for deformation of the store or suspension equipment, broken or bent fins, and any evidence of the store making contact with the aircraft structure or other stores (see Figure 3-2).

Figure 3-2: Post Flight Inspection [13].

3.2.1 Flying Qualities Flight Test Techniques

Flight controls should be instrumentation to give the pilot feedback on flight control positions in the cockpit for use during the execution of the test maneuvers. If there is no instrumentation, then a training flight should be conducted to calibrate control positions, particularly the rudder pedals. If there are rudder limits for a store configuration, which are common for flight with asymmetric stores, then the pilot must have confidence either from access to instrumentation, or from practice, that the flight test maneuvers can be executed without exceeding aircraft limits.

Testing begins with taxi and takeoff. For heavy stores or stores with very tight clearances, observation of stores movement and oscillation during the taxi should be accomplished. Any significant pitch oscillations caused by store loading could lead to pilot induced oscillations during takeoff.

Longitudinal dynamics are evaluated with a 1-g pitch doublet that will show the short period characteristics of the aircraft when loaded with a store. A rudder doublet is used to test the lateral-directional dynamic response of the aircraft and susceptibility to Dutch roll. Both maneuvers should be performed with stability augmentation on and off, if it is safe to do so. The number of overshoots should be less than seven for an acceptably damped system. If oscillations increase in amplitude the system is unstable. If this occurs, reengage pitch or yaw dampers if able and discontinue testing.

Rolls are performed at 1 g and in both directions in a buildup approach to nominally +/- 60 degrees (+/- 30 degrees for large aircraft, and possible higher limits for some fighters) without stability augmentation, if possible. The rolls should be done away from the store first to be sure that there is enough roll control authority to stop the roll [14].

Steady-heading sideslips to full rudder deflection, or aircraft limits, are performed to test directional stability and are usually performed with stability augmentation on. Rudder forces should increase as sideslip angle increases. Any lightening of rudder forces with increasing sideslip angle is an indication of decreasing directional stability and the maneuver should be terminated. This flight test technique is usually not used in the power approach configuration [14].

3.2.2 Loads Flight Test Techniques

Ground loads testing is sometimes performed to determine loads when towing the aircraft. Landing gear instrumented with strain gauges is required for this testing. Landing loads may also be required to determine the ability of the aircraft structure to handle landing loads in a heavy stores configuration.

In flight, wind up turns, loaded rolls, and pushover maneuvers are used to gather loads data. Loads test points build up from 80 percent to 100 percent using a baseline of +1 g. The mid-range test limits are calculated using the difference between the maximum value and 1.0. Loads test results should be compared with predicted loads before proceeding to the next test point. Any result that shows significant differences from predicted values requires expert evaluation before proceeding further with flight testing.

Wind up turns are performed to the maximum symmetric g limit. The test point should be terminated if any stick force lightening is observed. Stability augmentation systems should remain on. The turn is usually done in the opposite direction of the anticipated departure, or in the direction opposite the store if flying with an asymmetric stores configuration. This will ensure that the aircraft will roll toward wings level flight if it departs controlled flight [14]. If departure is not a concern, turn toward the store to set up for the loaded roll.

Loaded rolls are performed at the maximum positive asymmetric g limit while maintaining maximum roll rate. For asymmetric loadings, the roll is generally performed away from the store to maximize stress on the store [14].

A pushover is performed to test the loads at the maximum negative symmetric g limit. This is followed by a loaded roll at the maximum negative unsymmetrical g limit. This roll is generally done in the direction of the store when loaded asymmetrically to maximize the stress on the store [14].

4.0 COMPATIBILITY FLIGHT PROFILES

In the previous section standard maneuvers for determining FQ and loads were described to allow the test team to determine that the *aircraft* can safely operate within the specified flight envelope for the specified store configuration. Captive flight profiles (CFP) are flown to determine if the *store* can handle the flight environment throughout the entire envelope while experiencing representative operational maneuvering. The purpose of the CFP is also to conduct a qualitative test of the aircraft handling qualities. Both MIL-HDBK-1763 [3] and MIL-HDBK-244A [4] are good references to consult when planning CFP tests.

Flying qualities, loads and CFP can be flown together. However the configuration of the aircraft cannot be changed during the CFP. Sometimes the CFP is broken into two flights to allow a buildup to the high q points. The first flight going to 80 percent of the maximum q, followed by landing and a check for loose panels, loosened or missing bolts, or damage to the store. The aircraft can then be flown to the maximum q point on a separate flight.

A chase aircraft with photographer should be included for CFP sorties. The chase aircraft should be an area chase, not flying in formation with the test aircraft, but available to look the aircraft over between high speed points and before landing. Where possible the test pilot should fly the CFP profile in a clean configuration (without stores) first so that changes due to stores loading are readily apparent.

4.1 CFP Flight Test Techniques

The initial test maneuvers are performed in the same manner as for the FQ and loads testing. A nominal CFP test point would include: steady heading side slips, pitch doublets, rudder doublets, roll performance maneuvers, a wind up turn and loaded rolls [14]. An example CFP test profile can be seen in Figure 4-1.

The maneuvers are flown in in a buildup approach beginning in the heart of the flight envelope (point 1) in the pattern shown in Figure 4-1 and moving through points 3 and 4 out to the maximum dynamic pressure (q) point where the Mach limit and the calibrated speed limit intersect (point 5). At the maximum q point, trim changes when using the speed brake should be evaluated and any excessive forces should be further evaluated.

Care must be taken when planning FQ, loads, or CFP points like those shown for test points 4 and 5 in Figure 4-1. An evaluation of the operational flight and employment requirements for the store should be used as a guide for what is necessary to be flown at high Mach numbers and high dynamic pressures. If an aircraft rarely flies and never employs the store at these points, testing at a more representative flight condition along with a carriage and employment limit in the flight manual may be more appropriate than conducting high risk test points.

Prior to landing, handling qualities should be evaluated in the approach configuration. The pilot should investigate trim changes when lowering gear and flaps and while performing turns and approaching stall warning. Other operationally representative tasks can be performed to test the compatibility of the store and aircraft. For example, aerial refueling, air-to-air and air-to-ground tracking tasks, and offset landing tasks. These tasks may highlight handling quality deficiencies and are often evaluated using a pilot questionnaire to determine the amount of pilot compensation required to complete the specified task. The Cooper-Harper scale which rates handling qualities from 1 to 10 based on a set of definitions for the amount of pilot workload and compensation for each task is a common tool for assessing aircraft handling qualities with and without stores [11, 15]. Other more tailored questionnaires have been developed to collect very specific handling qualities data.

The culminating maneuver in the CFP is the speed soak test shown as point 6 in Figure 4-1. This test point is flown at 0.9 Mach or the maximum allowable airspeed at 1000 ft. AGL for at least 30 min. This maneuver tests the store endurance and response to vibration. Any observation of unexpected limit cycle oscillation, or flutter, requires immediate termination of the test point.

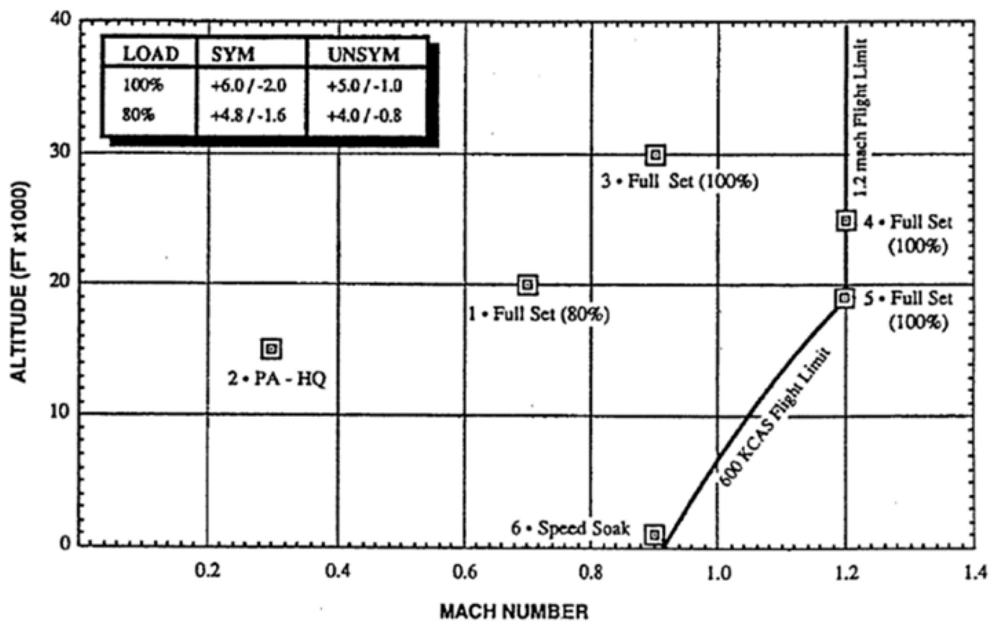

Figure 4-1: Notional Captive Flight Profile [16].

4.2 Safety Considerations

A practice flight should be scheduled to allow the pilot and control room team to become comfortable with the profile and the flight test techniques. The following safety measures should be considered for loads, flying qualities and CFP test sorties [14]:

1) Utilize a buildup approach
2) Minimize high-g points per mission
3) No elevated g rolls below 5000 ft. AGL
4) No inverted negative g push overs below 10000 ft. AGL
5) -1 g loaded rolls will start inverted and finish after 180 degrees
6) Load limits should be identified for each maneuver and monitored
7) Communications terminology between aircraft and control room should be concise and clearly defined
8) Test team should have predictions for every test point
9) Safety chase should be used for high-risk test points

5.0 CONCLUSIONS

When a new store or combination of stores is planned for an existing aircraft, ground and flight testing is required to determine the compatibility of the store/aircraft combination when operated throughout the flight envelope and while performing operational maneuvers. The tests are designed to determine whether the aircraft, when flying with the store, can still takeoff, land, and perform its operational mission without damage to the aircraft and without causing hazardous flying conditions. Testing should also determine whether the store can tolerate the flight environment.

Performance and flying qualities testing for stores carriage is among the most tailored of all flight test activities. A performance and flying qualities test program can range from many sorties over many months for a new program to a single flight that combines both FQ and loads and a CFP profile. Therefore it is incumbent on the test engineer to bring together the modeling and simulation, wind tunnel results, and similar previously certified stores data to design a test program that ensures that the most critical configurations are tested in the most taxing conditions expected during operational use.

6.0 REFERENCES

[1] NATO STO AGARDograph 300 Vol 14, (2005) Introduction to Flight Test Engineering, Neuilly-sur-Seine, France, July 2005.

[2] NATO STO AGARDograph 300 Vol 29, (2014) Aircraft/Stores Compatibility, Integration and Separation Testing, Neuilly-Sur-Seine Cedex, France, September 2014.

[3] MIL-HDBK-1763, (1998), Aircraft Stores Compatibility: Systems Engineering Data Requirements and Test Procedures, US Department of Defense, dated 15 Jun 1998, USA

[4] MIL-HDBK-244A, (1990), Guide to Aircraft/Stores Compatibility, US Department of Defense, USA, dated 6 April 1990.

[5] MIL-STD-464C, (2010), Electromagnetic Environmental Effects, Requirements for Systems, US Department of Defense, 1 Dec 2010.

[6] Seek Eagle Mass Properties Measurement, n.d., photograph, viewed 14 Apr 2016, <www.eglin.af.mil/photos>.

[7] FOTD and the GBU, n.d., photograph, USAF Test Pilot School, Stores Certification Lecture, 14A, page 26, 2014.

[8] Stewart, LCDR, USN, (2004), The Impact of the USS Forrestal's 1967 Fire on United States Navy Shipboard Damage Control, Master of Military Art and Science Thesis, U.S. Army Command and General Staff College, Fort Leavenworth, Kansas, 2004.

[9] 1967 USS Forrestal fire, n.d., photograph, viewed 14 Apr 2016, <https://en.wikipedia.org/wiki/1967_USS_Forrestal_fire>.

[10] J-PRIMES, (2010), 46th Test Wing Fact Sheet, SAF/IA, Washington DC, March 2010.

[11] MIL-HDBK-1797, (1997), Flying Qualities of Piloted Aircraft, US Department of Defense, 19 Dec 1997, USA.

[12] Eurofighter Paveway-IV-l, n.d., photograph, viewed 14 Apr 2016, <http://htka.hu/2015/07/20/htka-hirhalom-2015-30-het/>.

[13] Post Flight Inspection, n.d., photograph, USAF Test Pilot School, Stores Certification Lecture, 14A, page 56, 2014.

[14] USAF Test Pilot School, (1995), Systems Phase Planning Guide, Edwards AFB, CA, January 1995.

[15] Harper, R. P., and G. E. Cooper, (1986), Handling qualities and pilot evaluation, Journal of Guidance, Control, and Dynamics, 9(5), 515-529, 1986.

[16] US Air Force Test Pilot School, (1991), Volume III, Systems Phase, Chapter 8: Stores Certification, Edwards AFB, CA, page 8.70, March 1991.