GENERAL FLIGHT TEST THEORY APPLIED TO AIRCRAFT MODIFICATIONS

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Any external aircraft modification has potentially far-reaching effects on the capability of the aircraft to succeed or fail in its mission. The authors take a systematic look at the effects that small changes can have upon the whole, with a series of examples that demonstrate why careful review of data or testing is often vital in the assessment of system modifications.

A new design aircraft program always includes an instrumented test to validate the analyses. But a modification program may rely instead on previously collected data for model validation. Such a program must adequately address the effects of the modification on the aircraft and its mission. The user must judge these effects for their desirability—especially when they degrade mission capability. But, to be judged, they must be fully understood. Reviewing historical data or conducting a test are two ways to validate the data by which these effects on aircraft capability are judged.

In this article, we address eight critical test and evaluation considerations for an external aircraft modification. The aircraft design problems covered here represent the fundamental characteristics by which aircraft capability is judged. These design problems, when not properly analyzed and tested (if required), have historically resulted in significant degradation of air worthiness. We define the subject area and explain the importance of each problem by discussing the rationale behind standard design practices and air worthiness and operational considerations for the fleet aircraft. Concrete examples illustrate each case. Although only effects to the C–130 aircraft are discussed in detail, these principles and observations apply to any aircraft.

Structural (Stress and Loads Analyses)

Rationale. When structural strength proof tests are not performed, it is a standard engineering practice to specify that aircraft modifications be designed for a 25 percent or greater static margin of safety using a factor of safety of 1.5. The modified airframe will then have the strength capability to be released to fly at 100 percent of design capability.

"In fact, the most prolific sponsor of research competitions is the federal government, and in particular the Department of Defense."

However, if analyses show that an aircraft has a margin of safety between 0 and 25 percent, then the aircraft must be tested with sufficient instrumentation to ensure a positive margin of safety for the ultimate design conditions in order to prevent flight envelope restrictions. Finally, if analyses reveal a negative margin of safety or failure occurs during testing, either the deficient structure must be redesigned or aircraft flight envelope restrictions must be imposed.

Air worthiness and operational considerations. Reduction of the flight envelope means the aircraft must be restricted in airspeed, symmetric or maneuver G-loading, sideslip, or payload to prevent a design load limit (DLL) from being exceeded. Limiting the C–130 flight envelope as a result of any modification will significantly affect the aircraft mission capability. This is to be avoided at all cost.

The ultimate result when an aircraft is not designed to standard engineering practice (or verified by test) is increased likelihood of component or structural failure. An example of this is skin surface antenna mounts that come off in flight due to repeated flights at high airspeeds. Structural modifications that pierce the pressure vessel and are grounded in the load-bearing components of the aircraft are a special threat. This is because those components, when they fail, have a tendency to cause the failure of other load-bearing structures. This domino (a.k.a. zipper) effect can result in the loss of an aircraft. The loss of a modified KC–135 aircraft in the early 1970s was probably attributable to such a failure in a fuselage-mounted radome. Another problem symmetric modification can create is asymmetric loading. As a result of even the most benign maneuvers, the modification may be subject to airloads that cause oscillations in the fuselage. This can result in fatigue failure of structures well forward of the modification. The Beech V-tailed Bonanza is a classic example of this; the shape of the tail caused fishtailing that eventually resulted in fuselage failure.

Pressurization

Rationale. Pressurization is directly related to the previous discussion. It is in its own category because it is a common and potentially catastrophic failure mode in modifications. Generally, when the aircraft pressure vessel is penetrated, for whatever reason, a full pressure test series (proof and leakage rate) is made on the aircraft. Following a significant modification, a full pressure test must be completed prior to

the first flight during which the aircraft will be pressurized. The pressurized portion of the aircraft must be capable of withstanding proof-pressure testing at a level 1.33 times the maximum setting plus tolerance on the safety valve. This test should be performed on each modified aircraft.

Air worthiness and operational considerations. The importance of verifying pressure vessel integrity is evident from the standpoint of the potential consequences of a modification failure which breaches the pressure vessel. Pressure vessel failures have the potential to cause the loss of an aircraft due to an explosive decompression. An example of this is the C–130 flying near Iceland that had a breach near the wing root; it lost most of the top of the center wing and some of the fuselage. This aircraft made it back safely; many crews have not been so lucky. With any depressurization there are additional safety hazards to the crew as well.

FLUTTER, BUFFETING, AND VIBRATION

Rationale. Airframe vibration comprises three distinct areas: flutter and aeroelastic instabilities, dynamic loads, and vibroacoustics. Flutter deals with dynamically unstable elastic coupling of the airframe with the air stream, and occurs primarily in the lowest frequency airframe elastic modes. Dynamic loads deal with the forced vibration resulting from buffeting, atmospheric turbulence (gust), landing impact, sharp maneuvers, heavy store release, and other factors, again in the lowest frequency airframe elastic modes. Vibroacoustics deals with the forced vibrations of the airframe in the higher frequency local modes as driven by jet noise, aerodynamic turbulence, unbalance in rotating equipment, propeller or rotor blade aerodynamic disturbances, gun blast, etc. They can also cause control problems (which will be discussed in the section on handling qualities).

Flutter is the dynamic instability of an elastic body in an airstream. Flutter speed (Uf) and the corresponding frequency (vf) are defined as the lowest airspeed and frequency at which a flying structure will exhibit sustained, simple harmonic oscillations. Flutter is a dynamic instability (self-sustaining and increasing) that may result in failure of the structure. In aircraft, the failure of a main structure generally results in the loss of the aircraft. Aircraft are designed such that their airframe flutter will occur at airspeeds and conditions outside the aircraft envelope by a safety margin of at least 15 percent. Modifications that change the vibrational modes of an aircraft cause the flutter speed to change.

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The frequency and airspeed at which flutter occurs generally increases with increased structural stiffness. However, many times increased stiffness in a structural component changes the vibrational frequencies of that component and result in changes of frequencies in the overall aircraft structures. These changes can cause unforeseen consequences such as vibration or flutter, and their effect must be evaluated by analyses or testing. Usually, a ground vibration test is made to determine changes in the vibrational modes of a modified airframe. These

modes are used to validate or update the structural dynamic analysis model that determines the flutter speeds and frequencies.

Buffet is the elastic structural response of the airframe in the lower frequency structural modes to aerodynamic flow separation or shed vortices. Flight surfaces (wings, tail surfaces, etc.) buffet due to the oscillating forces as flow separates and reattaches over local areas. Buffet also occurs when surfaces downstream of flow separations are elasticity excited by the flow turbulence or by shed vortices. If buffeting occurs or if it is considered likely (there is no analytical procedure to predict these phenomena), the surface must be instrumented and flight tested. If testing shows surface loading outside the design load limits, the modification must be redesigned or the aircraft restricted.

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Vibration is the elastic response of the higher frequency modes of the airframe to the boundary layer turbulence, jet noise, and other high-frequency load and pressure oscillations. The primary source of vibration excitation in propeller aircraft is the pressure field that rotates with and flows aft of the propeller. It can result in fatigue failure of structures, particularly lightweight structures directly in the slipstream, such as wing flaps. Vibroacoustic measurements are made in general locations around the airframe, in specific locations of known problems, or in locations where severe flow disturbances are suspected.

Air worthiness and operational considerations. Flutter is a special concern for the C–130 empennage and can be a problem for any wing- or empennage-mounted modification. The A model of the aircraft was analyzed with a 15 percent flutter safety margin, but exhibited approaching flutter during high-speed flight. The aircraft was limited in airspeed due to this problem. The B model was redesigned with greater rudder and elevator tip weights to change the frequency of the surface bending and fuselage torsion and get back to the 15 percent safety margin. Any modification that changes the fuselage torsion or fin-bending modes has a potential to cause flutter in the C–130 empennage. Because of this, special care should be taken to ensure that modifications do not negatively affect the aircraft's flutter safety margin. With the advent of high-speed digital computers and the accompanying analysis tools, the ability to examine this phenomena during the modification design phase has been greatly enhanced.

The C–130 wing modifications result from the long-term vibrational effects on the airframe. The wing structural components were so weakened by vibration and stress that a couple of aircraft were lost and the entire fleet had to be restricted until modifications could be made.

All airframes are subject to some degree of buffet, higher level boundary-layer turbulence behind flow obstructions, and shed vortices. These loads cause structural problems in particular circumstances where elastic airframe modal frequencies are coincident with the frequency content of the aerodynamic excitation. When high frequencies are involved (vibroacoustics), the failures are often

rapid. Blade antennae are particularly sensitive to this type of excitation, and if located in regions of disturbed flow, they often separate from the aircraft. Even when these effects are not dramatic, aeroacoustic fatigue caused by buffeting is a serious problem for modified aircraft. This is demonstrated by structural cracking (a hole) on the fuselage of a C–135 (No. 4128, <30 flight hours after modification) caused by the separated flow behind a radome.

HANDLING QUALITIES

Handling qualities include static stability, tail plane control margins, mass properties, and dynamic stability.

Rationale. Handling qualities comprise many of the specific qualitative and quantitative areas involved in flight. Any modification to the exterior of an aircraft may affect the static or dynamic stability and control of an aircraft as a function of the modification's lift and flow perturbation characteristics. In general, a modification behind the center of lift will increase stability; conversely, one forward will decrease stability. Increased stability results in an aircraft that responds more sluggishly, with higher control forces for trim and maneuvering but with higher dynamic frequencies and more sensitivity to gusts. The opposite effects occur with decreased stability.

A modification ahead of or near a flight control surface can affect low- and high-speed control margins through vortex shedding onto the flight control surface. These effects can result in loss of control and are special concerns with the C–130 elevator. In flight test, the C–130A elevator was found to have a lack of effectiveness during landing. The chord was increased by 133 percent to correct this problem.

As previously mentioned, flutter, buffeting, and vibration can affect handling qualities. This is caused by the uncompensated motion of the flight control surfaces relative to the airflow. For instance, an elevator rotated upward is expected to cause an aircraft to climb. Deflection of the horizontal stabilizer caused by buffet, flutter, or vibration can result in the elevator providing a nose-down rotation. Asymmetric bending of the horizontal stabilizer from flutter, buffet, or vibration can cause a roll or yaw. In general, remedies for flutter, buffet, and vibration are also remedies for these types of handling problems. These are usually high-speed problems and rarely affect the C–130.

There are other problems related to buffeting. Shed vortices that cause buffeting can be helpful; for example, the C–130's overblown wing is created by propeller vortices. In terms of handling qualities, vortices can also worsen handling qualities. High-energy air striking the elevator on the bottom surface can cause an uncontrollable pitch increase. This could be especially critical during a C–130 assault takeoff or landing, or during a stall.

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A condition related to buffeting, called blanking, is caused when the air flowing over an aerodynamic surface is reduced by an object forward of the aerodynamic surface. This can result in

an uncontrollable pitch situation. Good examples of this phenomenon are exhibited in the stall of high-tailed aircraft such as the C–141.

Air worthiness and operational considerations. The most important consideration is that a modification will not degrade current overall aircraft flying qualities. Secondarily, a modification should not significantly change the flying qualities. In the first case, the aircraft mission may be compromised by aggravating emergency and normal situations with bad flying qualities; in the second, an aviator must be retrained to cope with a change in the handling feel of the aircraft. Anything that decreases the elevator control margins is a potential problem on the C–130. If control margins are grossly affected, the aircraft can display an increased tendency to depart controlled flight.

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The normal corrective action for degraded flying qualities is to restrict the aircraft's envelope. Minor changes in handling qualities can be accommodated by training programs and new technical orders.

High-altitude handling qualities, especially those related to dynamic stability (Dutch roll and phugoid) have a direct impact on passenger and crew comfort and are critical to aircraft controllability. The C–130 is not equipped with a yaw damper (which compensates for dynamic stability problems). Although Dutch roll is not a current problem in the C–130, a significant modification aft of the center of lift could decrease the aircraft's dynamic yaw stability. Depending on its severity, this would cause an altitude restriction or require a change to the modification.

Stalls, Air Minimum Control Speed, and Dynamic Engine Failure

Rationale. Stalls, engine-out flight, and dynamic engine failure are primary concerns because of potential negative handling qualities. A modification not mounted on the wing is not expected to affect the lift of the wing, but the effect of the modification on the empennage could reduce control margins to the point at which the aircraft departs controlled flight. More specifically, during low-speed flight, the loss of elevator effectiveness because of blanking or buffeting could cause a pitch up of the aircraft or a deeper, less recoverable stall. Asymmetric shedding from the modification could result in yaw forces that increase the likelihood of a spin or that decrease control during an engine propulsion emergency.

During engine-out flight, the effect of a modification could be increasing control pressure and deflection requirements because of airloads against the modification with increasing yaw. In addition, the uneven effects of sideslip angles on a symmetrical modification will result in an asymmetrical load on the aircraft. These loads, dependent on airflow patterns, could be helpful or harmful.

Air worthiness and operational considerations. The C–130 is a four-engined aircraft that is capable of flight on three or even two engines. It is not uncommon

to experience engine failures during flight. In the last five years, two aircraft have experienced dual engine failures in flight and have safely recovered. In these situations, the safety of the aircraft is dependent on control margin and air minimum control speed. Any reduction in control margin increases the air minimum control speed and reduces the chance an aircraft can be safely recovered. Engines also tend to fail at high power settings (takeoff and landing, low speed); dynamic failures are grossly affected by control margin and by aircraft stability margins.

Although the C–130 is a very forgiving aircraft and easy to recover from a stall, stalls have been the cause of some C–130 mishaps. Two types of stalls are possible in a C–130: a normal wing stall and a rudder fin stall. In a wing stall, the aircraft angle of attack (AOA) exceeds the capability of the wing to generate lift. The wing loses lift and the aircraft stalls. Recovery is accomplished by releasing back pressure to decrease AOA and increasing engine power. If back pressure is not released, the stall can be exacerbated, which will result in an increased loss of altitude. The elevator is usually effective even after the wings have stalled. If airflow around the elevator prevents the pilot from rotating the aircraft to a lower AOA, the stalled condition will continue until the pilot can force the nose over, or the aircraft hits the ground. If while the aircraft is in a stall, and yaw is applied either through a modification's asymmetric vortex shedding or the rudder, the aircraft can spin. C–130s have spun; they do not recover!

A rudder fin stall is a medium-speed phenomena in which the aircraft vertical stabilizer is stalled. During normal rudder use, the rudder is self-centering due to air loads; force is required to yaw the aircraft. During a fin stall, the aircraft is flying sideways with a high rate of yaw; force has to be applied to the rudder to make the aircraft fly straight again.

PERFORMANCE (DRAG)

Rationale. The main effect on performance for nonengine modifications comes from changes in drag. Increases in drag can degrade an aircraft's mission capability by reducing airspeed, ceiling, range, payload, and increasing takeoff distance. Drag comes in three main varieties: parasite, induced, and Mach.

Parasite drag is the drag produced by the modification just because it is on the aircraft and is caused by profile and interference drag. Profile (a.k.a. form) drag is caused by the air hitting the modification—skin friction and pressure. Interference drag is the drag caused by flow-field interference from interactions of the surfaces near and connected to the modification. In subsonic flow, interference and pressure patterns can move forward of the surface. Parasite drag increases with increasing airspeed.

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Induced drag is caused by the creation of lift. Vortex propagation from a structure is basically caused by the lift induced by the structure. These vortices change surface pressure distributions and cause an increase in drag. These vortices result

in the previously mentioned buffet. Induced drag is an inverse function of airspeed; it is the greatest at low airspeed.

Mach drag is mainly seen at the C–130 propeller, although it is possible at high speed on curved surfaces or in the engine flow field. Mach drag is caused by air flowing over a surface near Mach 1. Mach drag is what causes the controllability, noise, and vibration problems associated with a runaway prop on a C–130. Mach drag is rarely a problem on the C–130, but its effect is many times greater than that of induced or parasite drag.

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If an aircraft's performance parameters vary from its baseline by a cumulative 5 percent, the mission design series (MDS) must be appropriately performance tested to produce updated performance charts. The aircraft's capabilities are defined in the performance charts. For example, an aircraft is charted to take off in 2,900 feet, but it really takes 3,050 (about 5 percent more) feet following a modification. Unless the aircraft performance data is updated to reflect the change, that aircraft may crash the next time the crew tries to perform a maximum effort takeoff from a 3,000-foot dirt strip. There is no leeway or forgiveness in the charts.

Air worthiness and operational considerations. Many variants of the C–130 are performance limited. The gunships (AC–130H/U) are limited by drag to their current firing altitudes. Increased drag may result in moving them lower into the threat, thus negating survivability improvements. The Talons (MC–130E/H) are primarily terrain-following (TF) aircraft whose TF flight profile calculations and commands are dependent on their drag. Increases in drag have the potential to significantly affect TF capability. Further, significant increases in drag will reduce top and cruise airspeed, ceiling, range, payload, and will increase takeoff distance. All these effects are capable of degrading mission capability and must be investigated when making external modifications.

Flow Field

Rationale. Dropping items from aircraft creates a dual hazard: one to the aircraft, the other to the dropped item. Whenever an external store (which can be jettisoned or dropped from an aircraft) is developed, it must go through a certification process (Seek Eagle). This is because it is not uncommon for streamlined bombs, even in benign conditions, to strike aircraft when they are released. Tactical airlift aircraft are a complication in the carriage of external weapons. In this case, fragile personnel and very heavy objects (>44,000 lb) are dropped from the back and, in the case of personnel, from the side doors. The complexities of this, in terms of flow field, are manifold, from the unmodelable (and in many cases unknown) interactions of a 44,000-lb road grader to the unretrievable (due to air loads) hung paratrooper.

Extensive airdrop tests and certifications are made on airlift aircraft prior to the first real (human or cargo) drop. Safety is the driving concern of these tests with

two objectives in mind: first, to prevent damage to the aircraft because a load doesn't exit properly (hangs, gets stuck, slow release, etc.) or because it strikes the aircraft, and second, to prevent damage to the load.

Modifications to an aircraft affect flow fields, as mentioned above. The other sections described how these flow fields can affect the aircraft itself. In the case of airdrop, these flow fields interact with the objects moving through the field. Objects in an airstream create flow fields, which affect the aircraft and airdrop items both ahead and behind them. This is because subsonic flows create pressure patterns (effects) ahead of the aerodynamic structure they are striking. This is why Pitot tubes on most very fast aircraft are placed on the tip of the nose and away from the aircraft. On slower aircraft, the forward progression of the pressure patterns (flow fields) is less; however, the larger the object and the greater its flatplate surface, the greater the forward effect. The Pitot system on the MC–130H and the gunship required extensive testing and recertification because of the changes in the design from the MC–130E and AC–130H.

Air worthiness and operational considerations. If the load doesn't exit properly, the aircraft can be lost. This has occurred to C–130s on four separate occasions in the past 20 years. If the load is damaged during drop, the mission is a failure. The MC–130H is a special case among C–130s since its nose radome causes the airflow around the paratroop doors, the cargo ramp, and the cargo door to be at a higher speed than on a slick C–130. Drop tests during development proved the design, which is significantly different than a regular C–130. In addition, the MC–130H is capable of airdrops up to 250 knots indicated air speed (KIAS); the "green" C–130 is normally limited to 150 KIAS. The AC–130U also has flow-field considerations because the primary method of in-flight egress is the right rear paratroop door. This door has been provided with an extended air deflector to allow safe egress.

Forward field effects from a large modification aft of the troop doors could greatly affect flow patterns around the door. This could produce problems for paratroopers by causing them to hit the side of the aircraft, by preventing D-bag recovery, and by preventing recovery of a hung paratrooper. Similar effects could prevent successful egress from an AC–130.

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Aft flow-field effects from a modification forward of the ramp and door could cause similar problems for paratroopers exiting the ramp and door, but could also affect the airdrop of heavy equipment and container delivery system loads. Heavy airdrops all require parachutes to deploy for extraction. Delays in parachute opening caused by flow-field effects could increase the time for load extraction, causing off-target drops or hung loads. The massive change in the center of gravity during a heavy airdrop makes for an unflyable aircraft if the load hangs. A hung 44,000-lb load would stand a C–130 on its tail. Increases in air velocity can cause deployment and extraction chutes to blow out, causing delayed or hung loads.

Electromagnetic Interference and Electromagnetic Compatibility

Rationale. Electrical and magnetic fields occur around the wiring (radiated) in an aircraft, and equipment may output interfering signals directly on common wiring such as the power lines (conducted). Dependent on the voltage, amperage, filtering, and shielding, the interference levels will vary and may prevent other electrical equipment from working correctly.

Air worthiness and operational considerations. The most commonly affected part of the aircraft is the navigation equipment. Air Force aircraft are not shielded in accordance with Federal Aviation Administration requirements, so it is not uncommon for portable electronic devices such as cassette recorders and compact disc units to cause problems with the navigation repeaters and the intercom. New equipment installations must always be tested for electromagnetic interference and electromagnetic compatibility (EMI/EMC) on each mission design series; the equipment itself should have been tested for EMI/EMC compliance during its development phase. The reason for this is that the wiring in each MDS is different. In one case, the modification wiring may be next to a high-frequency radio wire bundle; in another, it might cross a transponder lead. It is also imperative that the wiring be consistent on each aircraft within an MDS, so that the interference issues are the same and only one aircraft of a given MDS needs to be checked.

Summary and Conclusions

It is clear that even a simple modification to an aircraft can result in disastrous consequences if adequate testing is not accomplished. It should also be apparent that such simple modifications require a complex analysis of the effects of the modification. When planning, developing, and producing modifications, keep these concepts in mind, and realize that the C–130, in all variants, is a relatively uncomplicated aircraft. When modifications are required for an aircraft which is fly-by-wire, control-by-wire, or significantly dependent on software and software-based systems for basic flight, the problems described can be magnified significantly in their complexity and effect.

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