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# Survey of Applications of Active Control Technology for Gust Alleviation and New Challenges for Lighter-weight Aircraft

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## Abstract

This report provides an historical survey and assessment of the state of the art in the modeling and application of active control to aircraft encountering atmospheric disturbances in flight. Particular emphasis is placed on applications of active control technologies that enable weight reduction in aircraft by mitigating the effects of atmospheric disturbances. Based on what has been learned to date, recommendations are made for addressing gust alleviation as the trend for more structurally efficient aircraft yields both lighter and more flexible aircraft. These lighter more flexible aircraft face two significant challenges: reduced separation between rigid-body and flexible modes, and increased sensitivity to gust encounters due to decreased wing loading and improved lift-to-drag ratios. The primary audience of this paper is engineering professionals new to the area of gust load alleviation and interested in tackling the multifaceted challenges that lie ahead for lighter-weight aircraft.


## 1. Introduction

This report provides a historical survey and assessment of the state of the art (SOA) in application of active control of aircraft encountering atmospheric disturbances in flight. Particular emphasis is placed on applications of active control technologies that enable weight reduction in aircraft by mitigation of detrimental effects caused by atmospheric disturbances. The intent of this report is to survey relevant systems that have been evaluated experimentally in wind tunnels or flight; also included are case studies of well-documented operational systems. Specifically excluded from this report are the myriad theoretic and simulation-based studies that have been conducted. This report is not intended to present an exhaustive survey; rather it is intended to be a concise presentation from which dominant historical themes, the SOA, and future trends can be assessed. The primary audience of this report is engineering professionals new to the subject area and interested in tackling the multifaceted challenges that lie ahead.

Understanding and modeling the response of an aircraft to atmospheric disturbances was recognized as a fundamental challenge early in aviation history. Aircraft modeling, atmospheric modeling, and airworthiness standards have co-evolved along with advances in aircraft capability and design. This advancement and co-evolution has occurred within individual design and analysis domains as well as an increase in the integration and coupling between these domains. The 1901 Wright gliders and early Wright flyers featured wing anhedral to provide resistance to rolling motion in response to side gusts (Etkin, 1980). The theory of aircraft encountering gusts, as it was understood in 1915, was included in the first National Advisory Committee for Aeronautics (NACA) report to Congress (Wilson, 1916). The NACA report contains aircraft equations of motion, representation of aircraft stability derivatives, and a simple model for aircraft response to encounters with discrete multi-dimensional disturbances (Etkin, 1980) (Wilson, 1916).

Prior to the early 1930s, airframes were designed to withstand flight maneuver load conditions alone; loads resulting from encounters with gusts were not considered for structural design of the airframe (Hoblit, 1988).The necessity of including aircraft motion in the gust response was also realized in the late 1930s (Hoblit, 1988). Incorporation of flexible, dynamic structural response was used beginning in the mid-1950s (Hoblit, 1988). Over the past few decades, the fidelity and accuracy of the models has improved, flight control systems have become more critical in the analysis, and the methods and techniques have been codified in terms of airworthiness standards (Hoblit, 1988) (Wright & Cooper, 2007).

The subject of this report exists amid a confluence of multiple traditional aerospace disciplines, namely: atmospheric science, aerodynamics, structural response, and flight control systems. There are many different types of objectives that a given application may have which can be satisfied by the implementation of an active control system. Some examples of the different objectives include alleviation of peak (maximal) load conditions, enhancement of fatigue life, and improvement in flying qualities (Honlinger, Zimmermann, Sensburg, & Becker, 1995). Additional active control technologies related to structural response with weaker, though not entirely separable, coupling to atmospheric disturbance objectives include deformation control, elastic mode control, flutter suppression, and flutter margin improvement (Honlinger, Zimmermann, Sensburg, & Becker, 1995).

Section 2 of this report provides the reader with a basic foundation in the modeling methods and technologies required for understanding the SOA in active control for mitigating atmospheric disturbances. The section also contains some discussion of pertinent airworthiness regulations and standards. Section 3 provides a discussion of the SOA operational systems, flight tests, and wind tunnel experiments. Section 4 presents conclusions and recommendations.

# 2. Gust Modeling and Aircraft Response

This section introduces the atmospheric disturbance modeling (referred to as gust or turbulence) and aircraft aerodynamic and structural modeling necessary to understand SOA practices and airworthiness standards. The background on modeling gusts and co-evolution of airworthiness standards is predominantly drawn from (Hoblit, 1988). Many educational books on aerodynamics, aircraft structure, and aeroelasticity contain a sufficient treatment of aircraft response to gust encounters to enable an understanding of SOA applications; thorough treatment of the topic is contained in few references, including: (Hoblit, 1988) (Wright & Cooper, 2007) (Bisplinghoff, 1996).

## 2.1 Modeling Gusts and Turbulence

Atmospheric wind can be considered a superposition of three types of flow: mean wind, waves, and turbulence (Stull, 2000). Mean wind is relatively constant with variation over the course of hours (Stull, 2000). Waves are regular oscillations of wind with variation on the order of tens of minutes (Stull, 2000). The turbulent component of wind is irregular, anisotropic, with quasi-random variations on the order of seconds to minutes (Stull, 2000). The period of variation for mean wind and waves are generally too slow to be considered for the dynamic response of an aircraft; the focus of the remainder of this section is on the approximations used for modeling the turbulent component of wind for exciting an aircraft response.

Atmospheric disturbance models often categorize the form of the disturbance into two idealized categories; discrete and continuous (Hoblit, 1988) (Wright & Cooper, 2007). Discrete gusts are generally considered deterministic, have simple forms, and are typically treated in the time domain (Hoblit, 1988) (Wright & Cooper, 2007). Continuous turbulence is treated as a non-deterministic distribution and is treated in either the time domain or frequency domain (Hoblit, 1988) (Wright & Cooper, 2007). Each form of the gust model is generally considered to be a spatial variation and invariant to both time and aircraft motion, though it is often convenient to express the gust variation as a temporal variation (Wright & Cooper, 2007).

Three forms of discrete gusts are of interest and are commonly encountered in application. The simplest form, and the first form historically implemented, is an instantaneous, uniform change in gust velocity known as sharp-edged or step gusts (Wilson, 1916) (Hoblit, 1988) (Wright & Cooper, 2007). Ramped gusts apply the change in gust velocity as a linear function (Hoblit, 1988). The 1-cosine gust models the gust form as a sinusoidal application of gust velocity, and more accurately captures the form of a solitary gust (Hoblit, 1988) (Wright & Cooper, 2007).

Continuous turbulence is represented as random variation in gust velocity. Two forms of continuous turbulence distributions are commonly encountered in application: Dryden and von Kármán (Hoblit, 1988) (Wright & Cooper, 2007). Both the Dryden and von Kármán distributions are defined by their power spectral density and lend themselves to application in either the frequency domain or time domain (via application of filtered white noise) (Hoblit, 1988) (Wright & Cooper, 2007). The Dryden and von Kármán distributions are both defined by a characteristic scale wavelength (typically a function of altitude) and the root-mean-square turbulence velocity (Hoblit, 1988) (Wright & Cooper, 2007). The von Kármán distribution is often regarded as a more accurate fit to measured atmospheric distributions, though the Dryden distribution has a more simple form and is easier to implement in the time domain as filtered white noise (Hoblit, 1988).

In addition to the idealized form of the modeled gust or turbulence, the applied dimensionality and spatial distribution (non-uniformity) of the disturbance also define a typical gust model. Gusts and turbulence tend to be isotropic in the real atmosphere (Hoblit, 1988) (Wright & Cooper, 2007). A notable exception to the isotropy simplification is turbulence due to thermals, which is anisotropic and has greater intensity in the vertical direction (Stull, 2000). Gusts and turbulence also tend to affect an aircraft non-uniformly in real encounters, for example, turbulence with length scales less than that of the wingspan of an aircraft will have variations in both direction and magnitude along the span of the wing.

Treatment of multi-dimensional and non-uniform gust distribution applications are rare in published literature, although some interesting results have been obtained. Analysis comparing one-dimensional (1D) and three-dimensional (3D) gust load modeling on the C-5A Galaxy aircraft (Lockheed Martin, Bethesda, Maryland) showed that 3D gust modeling decreased wing loads and increased horizontal tail loads; these results were partially verified through flight-testing (Eichenbaum, 1975). Analysis comparing 1D and 3D turbulence on the L-1011 TriStar aircraft (Lockheed Martin, Bethesda, Maryland) showed that 3D gust modeling decreased wing bending and shear loads and significantly increased wing torsion load due to excitation of the first antisymmetric bending mode (Hoblit, 1988). This result is significant in that it shows how neglecting the dimensional cross-correlation of gusts fails to predict important responses of the aircraft to 3D gusts. Experimental L-1011 flight response data compared better with a non-uniform gust model (Johnston, 1979). In a simulation study of the B-2 Spirit aircraft (Northrup Grumman, Falls Church, Virginia), it was found that a uniform spanwise gust distribution was predicting larger loads than a non-uniform gust distribution (Crimaldi, Britt, & Rodden, 1993).

## 2.2 Modeling Aerodynamic and Structural Response

Atmospheric disturbances influence the aerodynamic loads acting on the airframe; in turn, the airframe structure reacts in terms of structural deformation and internal loads. The aerodynamic modeling for gust response has evolved from modeling the quasi-steady response to incorporating both steady and unsteady effect. Similarly, structural modeling for gust response has evolved from modeling the aircraft as a rigid structure to incorporating flexible dynamic structural response. The structural and aerodynamic coupling mechanism is the study of aeroelasticity. The ensuing dynamic aircraft motion and control system response is the study of flying qualities and flight control systems. Even cursory treatments of each of these traditional disciplines are beyond the scope of this report. It is important that adequate aircraft simulation fidelity be achieved to properly propagate the effects of a gust encounter. For example, application of a vertical 1-cosine discrete uniform gust is easily incorporated in many modern simulations; application of a three-dimensional gust, non-uniformly varied over a flexible airframe is beyond the capabilities of many modern simulations that were not built explicitly for that purpose.

### 2.3 Airworthiness Regulations and Standards

In the United States the first civil airworthiness requirements explicitly relating to gust response were released in 1934 (Civil Aeronautics Board, 1934). Those requirements specified the computation of an aircraft response to a discrete sharp-edged gust acting normal to the flight path and acting separately on wing surface and tail surfaces; the aircraft structure was assumed to be rigid and the effects of aircraft motion were neglected (Civil Aeronautics Board, 1934). The regulation was modified in 1937 to attempt to capture the effects of the rigid body motion of aircraft by modifying the prescribed gust form to a linear-ramped type based on the specific parameters of the aircraft (Bureau of Air Commerce, 1937). The gust form was again modified in 1956 to a 1-cosine form to more accurately reflect aircraft responses to gust encounters measured from flight data (Civil Aeronautics Board, 1956).

Present airworthiness requirements for gust loads were last modified in 1996. The requirements specify the use of both discrete and continuous gusts (Federal Aviation Administration, Section 341, "Gust and Turbulence Loads," 1996). Continuous gust modeling was added to the FAR in 1980 (Federal Aviation Administration, 1980). The discrete 1-cosine pulse was modified in 1996 to represent a gust tuned to the aircraft response, specifically by requiring the use of dynamic loads analysis along with various lengths of gusts to determine critical gust conditions (Federal Aviation Administration, Section 341, "Gust and Turbulence Loads," 1996). This change to the discrete gust requirements effectively harmonized the Federal Aviation Regulations Part 25 with the Joint Aviation Requirements Part 25 of Europe (Federal Aviation Administration, FAA Docket No. 27902, Amendment No. 25-86, 1996). A summary of the changes in required gust form and the aircraft response modeling is provided in table 1. Current design load requirements for gusts and turbulence are determined by a uniform distribution of the gust velocity; although, as discussed previously, analysis of the response to non-uniform gust encounters could yield significant differences.

Table 1. Summary of United States Civil Airworthiness regulation maturation.

| Airworthiness regulation (year) | Gust form description | Aircraft response |
|---|---|---|
| CAB: Aeronautics Bulletin No. 7a (1934) | Discrete, 1D, sharp-edged | No dynamics |
| CAR: Part 04 (1937) | Discrete, 1D, ramped | Rigid body dynamics |
| CAR: Part 04b-3 (1956) | Discrete, 1D, 1-cosine | Rigid body dynamics |
| FAR: Part 25 (1965) | Discrete, 1D, 1-cosine | Rigid body dynamics with flexible structure |
| FAR: Part 25 Appendix G (1980) | Continuous, von Kármán | Rigid body dynamics with flexible structure |
| FAR: Part 25 (1996) | Discrete, tuned 1-cosine | Rigid body dynamics with flexible structure |

## 3. State-of-the-Art Applications

The SOA in application of active controls to mitigate gust response has been organized into three distinct groups for this report: operational aircraft, flight test experiments, and wind tunnel experiments.

Each group is presented separately in sections 3.1, 3.2, and 3.3, respectively, each in roughly chronological order.

## 3.1 Operational Aircraft

Several aircraft have been developed, or have been modified, to use advancements in active control systems to mitigate the effects of gusts.

The Lockheed C-5A is one of the earliest examples of an aircraft incorporating active control to alleviate the detrimental effects of atmospheric disturbances. The C-5A aircraft suffered from fatigue life problems related to wing bending loads (Globalsecurity.org). Several load alleviation systems were evaluated on the C-5A aircraft, including a maneuver load alleviation system and a passive alleviation system that simply biased the aileron deflections upward to reduce wing bending load (Disney, 1975). Eventually the Active Lift Distribution Control System (ALDCS) was developed after a C-5 wing fatigue test program indicated a need to reduce wing stress during both turbulence encounters and normal maneuvering (Disney, 1975). The ALDCS system used dedicated forward and aft vertical wingtip accelerometers and the existing inertial reference system to determine wing bending and torsional motion. The ALDCS interfaced with the existing stability augmentation system to actuate the ailerons and inboard elevators. The ALDCS system reduced the wing root bending moment by more than 30 percent, while not exceeding 5 percent torsional increase (Hargrove, 1976). The system was implemented with no significant reduction in stability or impact to handling qualities (Hargrove, 1976). The ALDCS system was eventually superseded by a wing structure modification; the structural modification added 18,000 lb (approximately 5.5 percent) to the empty weight of the aircraft (Globalsecurity.org).

The Lockheed L-1011-500 aircraft was the final derivative of the L-1011 family. The -500 variant included an Active Control System (ACS) that enabled a 5.8-percent increase in wingspan accounting for an estimated 3-percent reduction in total drag (Johnston, 1979). The incorporation of ACS to enable the wingspan increase eliminated the need to increase the aircraft empty weight by 1.25 percent (Johnston, 1979). The ACS system was developed to provide maneuver load alleviation (MLA) and gust load alleviation (GLA) without significant structural modification (Johnston, 1979). The sensor and actuation requirements for the ACS were similar to those used for the C-5A ALDCS. Wingtip and fuselage forward and aft vertical accelerometers as well as fuselage pitch gyroscopes were added to the aircraft to support the ACS. The horizontal stabilizers and ailerons were used for control effectors. The effects of the ACS on handling qualities were negligible.

The B-1 Lancer aircraft (The Boeing Company, Chicago, Illinois) employs a ride quality enhancement system that suppresses structural vibrations that are aggravated by the presence of gust disturbances (Honlinger, Zimmermann, Sensburg, & Becker, 1995) (Vartio, Shimko, & Tilmann, 2005) (Wykes, Mori, & Borland, 1972). The Structural Mode Control System on the B-1 Lancer actively suppresses the unfavorable motion at the pilot station using dedicated active canard-like control surfaces and a co-located accelerometer. The B-1 structural suppression system is fail-safe: the structural integrity of the airframe is maintained if the system fails, however, the flying qualities will be reduced. The total weight savings attributed to implementation of the active system, as opposed to adding structural stiffness, is approximately 9100 lb (Honlinger, Zimmermann, Sensburg, & Becker, 1995).

The B-2 Spirit aircraft has low wing loading and near-neutral pitch stability, making it susceptible to atmospheric disturbances (Britt, Volk, Dreim, & Applewhite, 1999). The gust loading requirements, as opposed to the maneuver loading requirements, size the structure of a significant portion of the inboard wing (Britt, Volk, Dreim, & Applewhite, 1999). The minimal vertical profile of the B-2 aircraft makes it less sensitive to lateral gusts (Crimaldi, Britt, & Rodden, 1993). The B-2 gust alleviation system uses an estimation of the gust component of the aircraft angle of attack computed as the difference between the measured angle of attack and the inertially-derived angle-of-attack estimate (Britt, Volk, Dreim, & Applewhite, 1999). The nominal inboard elevons and a dedicated gust load alleviation surface (GLAS) at the centerline of the aircraft are used for gust response (Britt, Volk, Dreim, & Applewhite, 1999). The B-2 GLA function pitches the aircraft into a gust to minimize normal acceleration and loads. Actuation of the GLAS and inboard elevons reduces the low-frequency rigid-body gust response and the inboard elevons excite the aircraft's first symmetric flexible mode. Thus, the outer elevons are simultaneously commanded out of phase to damp this mode. In certain flight conditions, the frequencies of the symmetric flexible mode and the short period are very similar (Britt, Volk, Dreim, & Applewhite, 1999). Overall, the closed-loop GLA "reduces incremental gust loads by up to 50%" (Britt, Volk, Dreim, & Applewhite, 1999).

Recent commercial aircraft have taken advantage of earlier advancements in active control for gust alleviation, although very little information is available in the public domain. The Airbus A320 aircraft (introduced in 1987) (Airbus, of the European Aeronautic Defence and Space Company EADS N.V., Netherlands) originally featured a Load Alleviation Function (LAF), which was later removed and was not incorporated into the Airbus A321, A319 aircraft, nor A318 aircraft. The LAF functionality has recently been reintroduced on some in-service A320 airplanes to allow a 1.3-percent increase in maximum takeoff weight (Kaminski-Morrow, 2008). The Airbus A330 aircraft (introduced in 1994) and the Airbus A340 aircraft (introduced in 1993) incorporated maneuver load alleviation systems as well as a flying quality enhancement system known as Comfort in Turbulence, or CIT. The objective of the CIT system is to increase the fuselage damping response (at 2.0 to 4.0 Hz) by actively controlling the rudder and elevators (Honlinger, Zimmermann, Sensburg, & Becker, 1995). The Airbus A380 aircraft (introduced in 2007) also features a form of GLA system (Norris & Wagner, 2005). The Boeing 787 aircraft (introduced in 2011) is reported to use a MLA system as well as a flying quality enhancement system (Norris & Wagner, 2009). The flying quality enhancement system incorporates "static air data sensors" to detect the onset of lateral and vertical turbulence and uses ailerons, spoilers, and elevons to counteract the turbulence (Norris & Wagner, 2009).

A summary of the use of active controls for mitigation of gust response on operational aircraft is contained in table 2. Each application has a unique objective and a unique set of aircraft constraints, which makes a quantitative comparison difficult. Early examples, including those applied to the C-5A, L-1011, B-1, and B-2 aircraft, were developed as a mitigation to design problems that surfaced late in the development process or were developed to enable capability enhancement. Recent commercial applications have incorporated active control technology from the onset of the design process, although details on the success and benefits of applying those technologies are lacking within publicly available literature.

Table 2. Summary of operational aircraft with documented active control systems to mitigate gust response.

| Aircraft | Principle objective | Sensors | Actuation | Critical improvement metric |
|---|---|---|---|---|
| C-5A | Load alleviation and fatigue life extension | Inertial | Symmetric aileron | Empty weight reduction 5.5% |
| L-1011-500 | Load alleviation for wing span extension | Inertial | Symmetric aileron and outboard spoilers | Empty weight reduction 1.25%<br>Drag reduction 3% |
| B-1 | Ride quality | Inertial | Canard-like vanes on nose | Empty weight reduction 4.7% |
| B-2 | Load alleviation and ride quality | Aerodynamic and inertial | Inboard elevons and dedicated surface | Gust load reduced 50% |
| A320 | Load alleviation | Inertial | Ailerons, spoilers, and elevators | N/A |
| A330 and A340 | Load alleviation and ride quality | Inertial | Rudders and elevators | N/A |
| A380 | Load alleviation and ride quality | N/A | N/A | N/A |
| 787 | Load alleviation and ride quality | Aerodynamic | Ailerons, spoilers, and elevators | N/A |

### 3.2 Flight Test Experiments

Early flight tests of an active flight control system on a small transport aircraft showed that turbulence loads were alleviated by roughly 7 percent when the autopilot was activated even though the autopilot was not designed specifically to reduce gust response (Payne, 1953). The flight tests also showed that small variations in autopilot sensitivity did not have a significant effect on load alleviation performance.

A flight investigation of a control system specifically designed to improve ride quality on a small transport aircraft demonstrated a decrease in normal accelerations and pitching velocity, but an increase in wing root bending moment (Phillips, 1957). Angle-of-attack feedback was used to control the flaps on the aircraft. The inboard flaps were deflected down while the outboard flaps were deflected up. This created a downwash at the tail, reducing the pitching moment and having little effect on the lift; however, the outboard flaps created a larger negative root bending moment than what was seen when no alleviation system was used. This alleviation also caused larger load magnitudes and frequencies on other parts of the structure, including the tail and aft spar, which could lead to fatigue problems. In larger gusts, however, the system was expected to have lower magnitudes of wing root bending moment; this was not tested. Finally, flight measurements using a bomber aircraft showed that at high altitudes a yaw damper alleviates loads in the vertical tail, while at low altitudes the load alleviation is much smaller because the aircraft naturally has higher damping of the Dutch roll motion at these altitudes (Phillips, 1957).

The use of active flight control systems to alleviate gust loads and enhance fatigue life was investigated in the 1960s as part of the Load Alleviation and Mode Stabilization (LAMS) program (Burris & Bender, 1969). The LAMS program was conducted by the United States Air Force (USAF) to demonstrate the ability of active flight control systems to alleviate gust loads and control structural modes on large flexible aircraft such as the Boeing B-52 and Lockheed C-5 (Burris & Bender, 1969). The LAMS program included a flight test demonstration on a B-52E test platform (Burris & Bender, 1969) and was extended, through analysis, to show generic utility using C-5A models (Disney, 1975). The LAMS program showed that a control system could reduce peak structural loads and structural fatigue damage rates without degrading basic aircraft stability and handling qualities (Disney, 1975).

Ride quality and gust alleviation was investigated by Dornier GMBH and DFVLR[1] between 1976 and 1982 through development and flight-testing the Open Loop Gust Alleviation (OLGA) system. The OLGA system was primarily focused on alleviation of aircraft response in the 0.3 to 1.0 Hz range; this range is particularly objectionable for ride quality and is often near the short-period flight mechanics mode. The open-loop nature of the system relied on measurement of the gust angle of attack through use of a fast and precise angle-of-attack aerodynamic sensor and an inertially-derived angle-of-attack estimation. Control was achieved through coordinated deflection of ailerons and elevators. Flight-testing revealed that the OLGA system unintentionally excited the wing bending mode due to a phase lag of 180 deg near the wing bending mode natural frequency. Increasing the digital frame rate and adding notch filters eliminated the problem. The OLGA system demonstrated a significant reduction in vertical acceleration response (an approximately 10-dB reduction) and a small reduction in pitch rate response (Bohret, Krag, & Skudridakis, 1985).

The German Aerospace Center (DLR) continued to work on ride smoothing and gust alleviation through development of the Load Alleviation and Ride Smoothing (LARS) system. The LARS system combined an open-loop component, primarily for rigid body motion, and a closed-loop component, primarily for damping the elastic wing-bending mode. The open-loop component was similar in function to that of the OLGA system. The closed-loop component used wingtip and fuselage accelerometers as feedback to damp the first wing bending motion. The closed-loop component operated within a narrow frequency range, and used the same control actuator as the open-loop system. The LARS system was flight-tested on the Advanced Technologies Testing Aircraft (ATTAS). Similar results to the OLGA flight results were obtained: a 10-dB reduction in vertical acceleration response, and the wing bending oscillation was damped and the overshoot was reduced by 20 percent (Hahn & Konig, 1992).

The Aerovironment, Inc. (Monrovia, California) Helios unmanned aircraft sustained catastrophic structural failure due to high dynamic loads associated with an unstable pitch oscillation that occurred during persistent flight with high wing bending (Noll, Brown, Perez-Davis, Ishmael, Tiffany, & Gaier, 2004). An encounter with turbulence initiated the event that ultimately resulted in loss of the aircraft. Analysis of the Helios aircraft showed very high sensitivity to encounters with even modest turbulence.

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[1] Dornier GMBH and DFVLR: Deutsche Forschungs- und Versuchsanstalt für Luft- und Raumfahrt, or German Test and Research Institute for Aviation and Space Flight (now DLR) (Deutsches Zentrum für Luft- und Raumfahrt, formally “German Center for Aviation and Space Flight;” the shorter translation "German Aerospace Center" is more commonly used in English-language publications).

Flight research has also included the testing of sensors for use in gust alleviation systems. An optical sensing technology referred to as LIDAR (light detection and ranging) has been developed and flight-tested to detect atmospheric turbulence ahead of an aircraft. Control systems and their effectors having some degree of lag, early detection of gusts provides ideal lead time before the turbulence disturbs the aircraft. Bogue (Bogue & Jentink, 2004) provides a good historical background on optical airflow measuring devices and covers flight test examples as early as 1971. To this point, LIDAR sensors have been tested in flight but not integrated with controls during flight test for gust load alleviation. In (Soreide, Bogue, Ehernberger, Hannon, & Bowdle, 2000) a coherent LIDAR system was tested up to 25,000 ft on a Lockheed Electra L-188C aircraft. Axial velocity measurements were made along a single line of sight (versus over a scanned area) up to 8 km (4.97 mi) ahead of the aircraft. Taking the lead time into account, the measurements correlated well with the local sensor data collected onboard the aircraft. In (Rabadan, Schmitt, Pistner, & Rehm, 2010), a more advanced LIDAR system was flight-tested on an Airbus A340-300 up to 39,000 ft in clear air, rain, dense clouds, and ice rain. Many LIDAR systems, including the system in (Soreide, Bogue, Ehernberger, Hannon, & Bowdle, 2000), are dependent on a high density of aerosols in the local atmosphere for their function. Higher altitudes and some areas around the globe do not have this concentration of aerosols. For this reason, a direct-detection short-pulse ultraviolet Doppler LIDAR was developed and flight-tested which can measure disturbance in aerosol-depleted regions by using molecular (not aerosol) backscatter. The system measures disturbances 50 meters ahead of the aircraft, providing 300 milliseconds of lead time, which is stated as sufficient based on the angular velocity and the maximum deflection required by the ailerons. Four line-of-sight measurements (±10° vertically and horizontally from the nose) are taken at 60 Hz, which provides more than enough information for 3D airspeed vector detection at 15 Hz. The LIDAR data compared very well with forward projections of the aircraft true-airspeed sensor along the four line-of-site directions when considering the attitude of the aircraft.

## 3.3 Wind Tunnel Experiments

Various approaches to gust load alleviation have been tested in wind tunnels. In most cases, experimental results show some level of load alleviation in the presence of simulated gusts. Each test described within this section uses different wind tunnel models, control techniques, and metrics to measure load alleviation, making it impractical to compare the performance from one test to another. For these reasons, the magnitude of gust alleviation is not included in the discussion.

### *3.3.1 Gust Generation Techniques*

Various gust generation techniques have been employed by way of wind tunnel testing. Discrete "sharp-edged gusts" and "gradient gusts" have been generated in wind tunnel testing using "screening and perforated plates" (Mickleboro, 1948). Continuous sinusoidal gusts are commonly generated by way of oscillating vanes or airfoils mounted upstream of the wind tunnel test section. The transonic Dynamics Tunnel at NASA Langley Research Center (LaRC) is equipped with such a system, known as the airstream oscillation system (Silva, Vartio, Shimko, Kvaternik, Eure, & Scott, 2006) (Scott, Castelluccio, Coulson, & Heeg, 2011). Continuous, random gust disturbances can be generated by use of a flapping banner (Abel, Perry, & Newsom, 1982). The gust characteristics resulting from the flapping banner can be modified by using different widths of banners and also two-dimensional grids (or screens) that have adjustable spacing between the vertical and horizontal members (Horikawa & Saito, 1986).

### *3.3.2 Recent Wind Tunnel Studies*

Numerous wind tunnel studies were conducted prior to the 1980s; this report summarizes the results of a number of select, significant wind tunnel studies conducted after 1980. One early study in the 1980s conducted at NASA LaRC found that a control law designed for flutter suppression also reduced wing loads due to gusts (Perry, 1981) (Abel, Perry, & Newsom, 1982). Two control laws were developed for an aeroelastically-scaled semispan model of a McDonnell Douglas DC-10. The first control law was developed using the aerodynamic energy method and the second using optimal control theory (Abel, Perry, & Newsom, 1982). An accelerometer was installed near the tip of the wing to provide vertical acceleration feedback. The wing's aileron was the only control effector. Strain bridges measured the bending and torsional loads on the wing (Perry, 1981) (Abel, Perry, & Newsom, 1982). By adding turbulence response experiments to the test plan, the first control law showed evidence of gust load alleviation, which was most likely due to it having more filter-mode damping than the second control law (Abel, Perry, & Newsom, 1982).

A study conducted at Kawasaki Heavy Industries, Ltd. (Japan) using a model 1/9-scale transport wing with aspect ratio of 10.5 showed bending moment reduction over a range of frequencies using a full state GLA control law (Horikawa & Saito, 1986). An arrangement of sensors and one effector (a single aileron) similar to that used in the NASA LaRC study was utilized. A similar test was also conducted, with three control surface configurations, including an inner aileron, an outer aileron, and a leading edge control surface, all located near the outboard section of the wing, using the same wing design (Matsuzaki, Matsushita, Miyazawa, & Ueda, 1989). Each surface was tested independently to determine its individual effectiveness on GLA performance. Optimal control theory was employed to minimize the mechanical energy in the elastic wing and the actuator command. Minimization of the first mode was the primary objective of the study. The results showed that the leading edge surface was not as efficient in GLA compared to the other configurations. In comparing the inner and outer ailerons, it was observed that the outer aileron suppressed the first mode better than did the inner aileron; however, it was also observed that the inner aileron was better at suppressing the second mode. Thus, the placement of control effectors with respect to modal node lines largely dictates their effectiveness in alleviating dynamic responses.

A series of wind tunnel studies characterizing the system response and active control characteristics of two SensorCraft (Air Force Research Lab) concepts have been conducted and are fairly well published. Two variations of conceptual SensorCraft models have been tested: a flying wing concept and a joined wing concept (Vartio, Shimko, & Tilmann, 2005) (Scott, Castelluccio, Coulson, & Heeg, 2011). Both concepts rely on active control for rigid body stability, load alleviation, and structural mode control to suppress unstable aeroelastic modes. Both concepts have been tested with aeroelastically-scaled wind tunnel models with rigid mounting and mountings that allow both pitch and plunge motion.

The flying wing concept wind tunnel model was a semispan model utilizing one leading edge control surface at the outboard wing section and four trailing edge surfaces along the span of the wing. The joined wing concept wind tunnel model was a full span model utilizing 13 trailing edge control surfaces: three on each main wing, three on each joined wing, and on the vertical tail support. Both models were similarly instrumented with accelerometers and gyroscopes for inertial measurement, strain gages for stress measurements, and a means of measuring the aerodynamic inflow (the flying wing tests used a traditional vane mounted upstream from the model; the joined wing model incorporated several leading edge stagnation point, or LESP, sensors along the leading edge of the model). Both models can be either rigidly mounted or mounted on pitch and plunge devices.

An optimal estimator and regulator (linear quadratic Gaussian) were designed to control the rigid body and flexible structural modes of the flying wing SensorCraft model (Vartio, Shimko, & Tilmann, 2005). The test was conducted with the wind tunnel model rigidly mounted to the wind tunnel wall (without pitch and plunge freedom). Overall, the test demonstrated successful active control: simultaneously on the model, the wing root bending moment was reduced, the first and second bending modes were dampened, and the pitch moment was controlled. While the results of the test showed that bending moment was greatly reduced, the measured reduction did not meet the a priori prediction; the authors suggest that deficient modeling of control surface effectiveness, actuator characteristics, and gust field are the principle causes of the unmatched results. Bending moment alleviation at the wing root using only the leading edge and outboard trailing edge control surface is feasible and achieved nearly the same bending moment reduction as using all the control surfaces, although larger surface deflections were required with fewer surfaces. Analytical predictions indicated that phase lead in the gust feedback would improve the ability of the control system to alleviate loads; however, the experimental results were inconclusive due to problems with the leading edge control surface actuator.

In a follow-on series of tests with the flying wing semi-span SensorCraft the model was mounted on a pitch and plunge device to allow the model to exhibit some rigid body modes (Vartio, Shaw, & Vetter, 2008). This series of tests evaluated controllers similar to those tested in the previous series. In this series, varying levels of explicit load alleviation in response to gust were evaluated, as well as the effect of using only the leading edge and outboard trailing edge control surface. The test found that incorporation of an explicit gust alleviation function reduced the critical wing bending moment significantly, and, similar to the previous study, found that use of only the outboard control surfaces was feasible for all objectives.

Fourteen different control laws were tested and evaluated in a series of wind tunnel tests using the joined-wing SensorCraft wind tunnel model (Scott, Castelluccio, Coulson, & Heeg, 2011). Classical control theory was used to develop the GLA control laws based on previous wind tunnel parameter identification and characterization tests. The best-performing control law utilized three strain gage inputs as feedback and four surfaces for control; this controller resulted in a 50-percent decrease in structural response while maintaining adequate robustness.

Leading edge stagnation point sensors were also employed on both SensorCraft wind tunnel models to determine their performance as feedback for gust alleviation (Mangalam, Mangalam, & Flick, 2008) (Scott, Castelluccio, Coulson, & Heeg, 2011). The use of LESP sensors enables “direct access to the aerodynamic forcing function, its magnitude and direction at any span station, and more importantly, provides control input with valuable lead-time compared to the structural response obtained with conventional techniques” (Mangalam, Mangalam, & Flick, 2008). The results within this work showed that additional feedback from the LESP sensors enabled a reduction in bending moment and a decrease in required control power when compared to the performance of only using inertial sensors.

Active control of the Semi-span Super-Sonic Transport (S4T) wind tunnel model was recently evaluated in a series of wind tunnel tests for the purpose of demonstrating flutter suppression, gust load alleviation, and ride quality enhancement (Silva, et al., 2011) (Moulin, et al, 2010). The S4T is an aeroelastically-scaled semispan model of a supersonic transport aircraft. The model contains three active control surfaces: a ride control vane near the nose, a midspan aileron, and an all-moving horizontal tail. Strain gages are used to measure the bending, torsion, and shear loads. Several control laws were developed, tested, and evaluated to assess their ability to singly and simultaneously manage flutter suppression, gust load alleviation, and ride quality enhancement. Silva reports limited success in meeting all objectives of control due to safety concerns regarding the model; he also provides references to numerous reports on the particulars of the control systems that were tested.

Fuzzy logic control was employed to demonstrate gust load alleviation on a high-aspect-ratio wing model with two control surfaces: an inner and an outer aileron (Shao, Wu, Yang, & Chen, 2010). The model was a semispan test wing rigidly mounted to the wind tunnel wall. An accelerometer was mounted in the wingtip for use as feedback in the control system. The control system reduced the gust response by 20 to 27 percent and performed similarly with both random and sinusoidal gusts.

# 4. Conclusions and Recommendations

Atmospheric modeling and aircraft response modeling are relatively mature and accurate technologies. Early wind tunnel experiments and test aircraft have shown a feasible path forward in understanding and managing gust encounters. Initial application of the active load alleviation technologies were implemented either to fix a developing problem or to provide enhancements to existing aircraft. Use of active control for mitigating the impact of atmospheric disturbances has matured to become a crucial element during the design of new aircraft. Weight savings have been realized through application of active control technologies to mitigate the detrimental effects of gust and turbulence encounters.

Various sensors, effectors, and control laws have been used and tested in relevant environments. Typically, atmospheric disturbances, or the structural response to gust, are measured by an air data system or inertial sensors or both. New technologies, such as leading edge stagnation point and light detecting and ranging, provide more lead time and are gaining acceptance through systematic development and testing. Control effectors typically include designated control surfaces, such as canards or a centerline control surface; or conventional, multipurpose effectors, such as flaps and ailerons. No single control law synthesis technique or methodology has proven superior; rather, many techniques have been demonstrated successfully. Various studies have also shown that closed-loop control intended for other purposes, such as an autopilot or flutter suppression, can indirectly help alleviate gust loads and improve flying qualities.

As aircraft have been refined and optimized for their missions, and the ability to predict and model those aircraft has improved, aircraft structures have become more efficient and the separation between rigid body and flexible modes reduced. This trend is anticipated to continue, leading to new challenges of controlling more flexible, lighter-weight aircraft through atmospheric disturbances. The separate objectives of flutter suppression, gust load alleviation, and flying qualities will need to be treated and addressed simultaneously. The Helios mishap exemplifies the challenges at the extreme of the present trend. Additional sensing and actuation requirements, beyond those already realized in current operational aircraft, will need to be developed. It is likely that the higher bandwidth control effectors will also be required for some applications. Control surface actuation will have to be coordinated to manipulate both rigid body and flexible modes that are observed simultaneously, without unintentionally exciting or aggravating other modes. Overall, multidisciplinary approaches to aircraft design will be crucial.

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