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Avionics: A "New" Senior Partner in Aeronautics

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The application of electronic devices to aviation, particularly to air vehicles, has given rise to the term *avionics*. This term is now widely understood. The extent to which the technology that it represents is pervading aeronautics, however, is much less so. Although avionics often refers only to mission equipment packages (MEPs), increasing use of the term vehicle management system (VMS) by practitioners indicates its broader usage, and both MEP and VMS uses of avionics are considered in this paper. Several specific engineering developments that have made the influence of avionics so profound for aeronautics are summarized. It is noted that the earliest applications were in the form of equipment add-ons to existing vehicle types. However, the benefits of exploiting avionics and the increasing need to rely on them have now reached a level that requires their capabilities to be accounted for at every stage of aeronautical vehicle system design. As a result, the integration of avionics into the aircraft development process is now a matter of primary concern. Further, with the power of present-day digital technology, the associated software has become as complex and crucial as hardware. After reviewing the growing number of functions for which the capabilities of avionics are being used, the additional impact of so-called smart materials and structures is introduced, and the implications of avionics for aircraft designers and aerospace engineering educators are discussed.

Introduction

NOT long after the emergence of aircraft as vehicles with serious potential for transportation, the need for electronics-based equipment became apparent. Air-ground-air communications (radio); navigation, instrument landing systems, and collision avoidance (radio beacons, radar, and transponders); and all-weather, blind-flying instruments (attitude gyros, weather radar, and artificial horizons) were among them. Thought of as equipment to be added to an existing aircraft type, the combination of electronics and their aviation applications gave rise to the appellation *avionics*. The marriage of certain avionics sensors, e.g., for attitude, altitude, and speed, with relatively slow-acting actuators for moving flight controls, and using feedback control techniques, led to "automatic pilots," i.e., autopilots. Although this could change the role of a pilot substantially, influence on aircraft design still was minimal, and autopilots could also be thought of as add-ons.

Two major aircraft/missile engineering developments changed the status of avionics drastically. The first development was more quick-acting powered actuators, usually hydraulic, originally thought of as boosting pilot force output. Subsequently, the frequency response capabilities of these boost actuators were raised to the point of acting as rapidly or more rapidly than any pilot. The second development was in automatic, i.e., without human intervention, computing capabilities, first analog, then digital. Taken together with evolutionary development of sensors and means to transmit signals/forces from cockpit to control surface, these two developments allowed avionics to begin to take their place in aircraft design in ways that influenced such basic flight mechanics considerations as the size of tail surfaces and acceptable aircraft mass characteristics.

This fundamental pervasion of the flight mechanics—or aircraft handling qualities—discipline by avionics can be thought of as the first major change in the status of avionics in aircraft design. It began with autopilots around 1917,[1] and grew with stability augmentation systems some 40 years ago, where it was most needed, in rotary wing aircraft developments. The second major change in the status of avionics in aeronautics is still underway. It is being driven, in essence, by the question: If avionics systems can be made sufficiently reliable and effectively redundant—including their digital processors—that designers can count on them to avoid catastrophic flight conditions, i.e., as regards attitude, angle of attack, airspeed, angular rates, why not rely on them to guarantee structural integrity, prevent aeroelastic instabilities, approach but not encounter engine compressor stall, etc.? As in other areas of intensive computer applications, software then becomes as complex and crucial as hardware, and the multifunction aspects raise choices such as limited function, dedicated systems vs multifunction, more generally capable systems. In any event, if these newer avionics systems capabilities are to be exploited in such fundamental ways as reducing aircraft structural weight and increasing available engine power, their integration with all aspects of airframe/engine design must be carried out at every stage—far from the original add-on concept to which the aircraft designers of yesteryear relegated avionics.

It will be noticed, particularly by those more expert in avionics system design and development, that my concept of avionics systems goes well beyond mission equipment packages (MEPs). Much closer to my definition are what many companies now call vehicle management systems (VMSs). The term VMS, in fact, itself implies the pervasive aspect of avionics integration. This aspect, the additional impact of so-called smart materials and structures, and their implications for the aircraft designer and aerospace engineering educator are discussed in this paper.

The pertinent literature is very large, and the references that appear here have been chosen as illustrative of the points being made. Far from being comprehensive, the list of references should not be viewed as typical, but eclectic.

Some Definitions and Categories of Avionics Systems

It should be admitted, at the outset, that the author is by no measure an avionics expert—either as regards MEP or VMS. The choice of my topic for this Dryden Lecture and its acceptance by the approving committee reflects my enthusiasm for the subject of integrating avionics capabilities into the conceptual and preliminary design of aircraft. It follows that my definitions may not always adhere to consensus usage; my hope is that a different viewpoint may prove useful. Reference here to "experts" and "consensus usage" should help to explain the quotation marks around the word "new" in the title of the paper. Anything that has been underway for more than half a century, as noted in an earlier paragraph, can only be new in some special, limited sense. What is new is avionics usage's unignorability at the earliest stages of design for such a wide spectrum of aircraft types and the increasing frequency of retrofitting upgraded versions of such systems in existing aircraft types.

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The components of avionics systems, as I see them, are not all electronic, and not all such systems contain all of the following components. Still, it is useful, I think, to note that avionics systems, by my definitions, have more than one of the following categories of components: sensors, transducers, linkages, processors, actuators, and power sources. Sensors respond to some physical (or conceivably chemical) quantity by converting it into a useful signal. Sensors are, in a general sense, transducers, but I propose restricting the use of the term transducer to mean devices that take a useful signal in one form and turn it into a useful signal in another form. Linkages are components that take useful signals at one location and move them to another location. Such transport of signals can be within the aircraft or from and to points external to the aircraft. It should be clear that only when forces and moments are transmitted are those linkages mechanical. Linkages involving digital processors require data buses, and compatibility must be ensured among such components. Processors may analyze, combine, store, or do all manner of useful things with signals and/or also model aircraft behavior, for comparative purposes. Such, usually mathematical, operations can be analog or digital. When, as is increasingly the case, digital operations are the designers' choice, software is also often an important avionics system component. Actuators are, in more general terms, transducers too; in my usage, however, they always provide the forces and/or moments, i.e., the muscle, to move aeromechanical parts of the system, usually control surfaces and, therefore, are differentiated from other system components. All may draw on power sources to some extent, but actuators, of course, the most, and linkages the least, if at all. Finally, machine interfaces with human pilots, although having some of the defining characteristics of other avionics system components, are also put in a class by themselves. Such include the devices that implement pilot inputs—pilot cockpit controls, such as engine throttles; rudder pedals; "stick," control "column," or sidearm controllers;—and those that inform the pilot as to situation—i.e., displays, including audio, as well as visual prompts. In summary, these avionics system components are as follows: sensors; transducers; linkages; processors; software; actuators; and human–machine interfaces: pilot controls and displays.

An example illustrating such components and their functions is shown in Fig. 1. This purports to be a pitch control system for a high performance fighter. The pilot's longitudinal sidearm controller motion is converted into an electrical signal by a motion sensor. That electrical signal is converted to an optical signal by an electrooptical transducer. Fiber optic linkages carry the optical signal to a processor. After being transduced back into an electric signal, it is amplified or attenuated there according to a second signal originating from an airspeed sensor (this may be simple gain changes), so that the aircraft's pitch response will be the same at all airspeeds (assuming this is a desirable characteristic). The signal from the processor then regulates a valve on a hydraulic actuator, which drives the aircraft's elevator, i.e., pitch attitude control surface. Several comments may be pertinent for this illustrative example. The electromechanical input valve on the hydraulic actuator might be considered a transducer, but for our purposes it is viewed as part of the actuator. Such an assembly is often called an integrated servoactuator. Fiber optic linkages (fly-by-optics; FBO) are used less often than electrical linkages (fly by wire; FBW) and in FBW systems there is no need for electrooptical transducers. Where fiber optics linkages are used it is usually because of their superior capabilities for carrying large quantities of information (high bandwidth) and insensitivity to electromagnetic interference (EMI), including that associated with lightning.

Although Fig. 1 shows only the hydraulic pressure source as requiring power, the electrical and optical signals shown also have been generated at some cost in power. Such are so low in their demands, as compared to actuators, as to be negligible for the purposes of this paper, although the weight of generators and batteries, if used as backup, is certainly not negligible.

It may be useful to categorize avionics systems according to the extent to which they need not or need to act faster than a human pilot, influence primary vehicle design variables, and the seriousness of the consequences of such systems functioning at less than their full capabilities. The close relationship, if not equivalence, of these measures should become evident as we continue. I propose that, the lower the category number, the less likely it is that system will influence an aircraft's basic design, although not without exceptions.

According to this scheme, Category I avionics systems would include communication functions (radio); navigation instrument landing and collision/terrain avoidance functions other than military contour of the Earth flying (GCA, RADAR, GPS); and for military aircraft "identification, friend or foe" and mission equipment packages (target acquisition, location, and tracking; weapon pointing). It is, I hope, understood that including such functions as weapon pointing refers only to generating the required information, or signal. Certainly the location and installation of a movable gun turret, for example, is best considered at early stages of the vehicle design and, in any case, is not considered avionic in Category I, or any other category.

Although Category I avionics systems can in many instances be added on well after the fundamental aircraft design is completed,

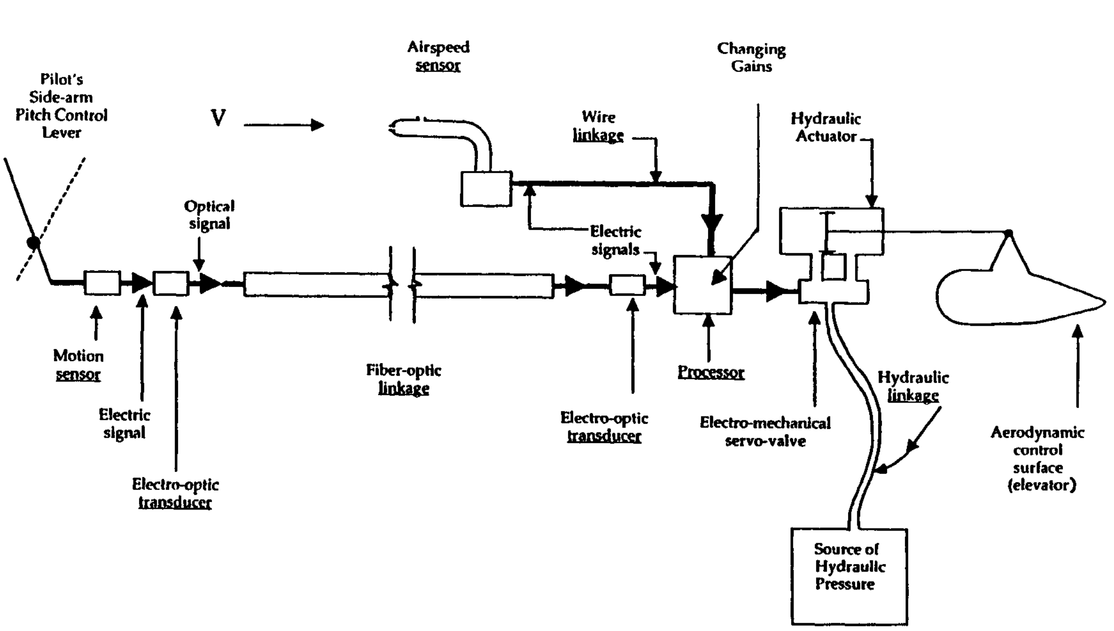


Fig. 1 Schematic of avionics components in a FBO flight control system for the pitch axis.

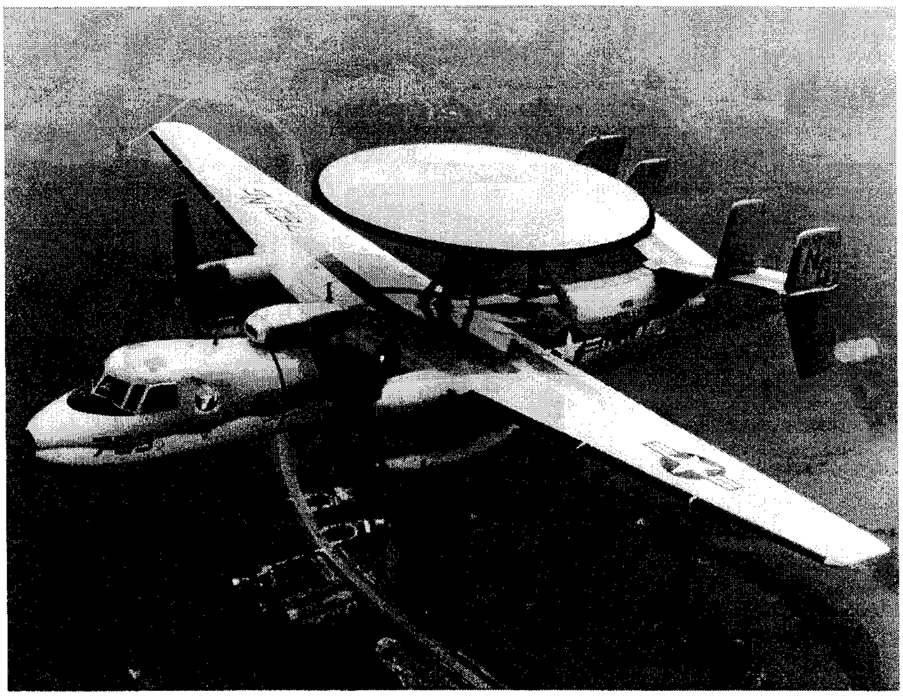


Fig. 2 Early warning E-2C aircraft.

those responsible for their integration still must provide 1) space within the airframe, 2) stress-free mounting points that limit the shock and vibration transmitted to this equipment, and 3) an environment of limited maximum temperatures and EMI and acoustic fields. Such must, of course, also be provided for all of the avionics categories, descriptions of which follow. Further, when transmitting/receiving antennas (the internal/external linkages) are involved, their locations should minimize interference with the signals to be sent or received and cross-talk to/from other electromagnetic (EM) sources. This is particularly challenging for aircraft designed to have low radar cross sections. These conditions for an acceptable environment for avionics components and a few others are listed: 1) space, 2) stress-free mounting, 3) limited transmittal of shock and vibration, 4) limited range of temperatures, 5) limited acoustic fields, 6) limited EM fields, 7) limited cross-talk between systems/components, and 8) acceptable outgoing/incoming radiation environment (for antennas).

It is noted, that when a MEP includes very large avionics components, e.g., antennas such as carried by AWACS or other early warning aircraft, e.g., Fig. 2, then structural modifications, aerodynamic control surface augmentation, and perhaps propulsive power modifications of a substantial nature can be required. Because these substantial modifications are still those that are often added well after the basic vehicle designs have been concluded, the associated avionics systems are thought of as being in Category IA.

Category II avionics systems are defined here as those that improve aircraft performance; hold heading, speed, attitude, or altitude (so-called autopilot functions); or increase structural fatigue life and/or reduce maximum maneuver loads. These systems, however, do so by changing what are, essentially, steady-state phenomena. The performance of Category II avionics systems, then, may have to be highly reliable, but not necessarily quick acting in the sense of having higher frequency response than a human pilot. From the list of functions just mentioned, it may be clear that the influence of some Category II systems could be profitably considered at the earliest stages of design.

Category III avionics are, in general, designed to deal with dynamic phenomena at frequencies up to those that a pilot could hope to deal with—say, from a fraction of a hertz to under 2 Hz. These phenomena include, in particular, flying qualities, i.e., stability and control of aircraft motion along the flight path. Their frequency range is established, for the most part, because the fundamental dynamic degrees of freedom are rigid body motions, although flexible structural modes and other nonzero frequency degrees of freedom may be involved. Stability augmentation systems (SASs) fall into this category.

Category IV avionics systems are those designed to modify the dynamic behavior of phenomena involving frequencies well beyond the response capabilities of human pilots, i.e., frequencies higher than approximately 2 Hz. The fundamental dynamic degrees of freedom will most often, in these phenomena, be flexible structural modes, although rigid body motion may be involved. Exceptions include 1) rotating systems, such as hinged rotor blades, in which rigid body motions out of the plane of rotation have natural frequencies close to the rotational speed and 2) control surface rotations restrained by stiff control systems, which, when they deflect other than as commanded, can move as rigid bodies, but at high frequencies. Systems to suppress unstable dynamic, aeroelastic phenomena, for example, are Category IV systems.

The requirements for reliability of Category I avionics systems, with the exception of the structural aspects of the IA category and those of Category II, are influenced by their low frequency characteristics. If actuators are involved, for example, they need only move rather slowly and so, with reliable indications for the pilot, even an actuator "hard over" failure might be switched off or otherwise countermanded by the pilot without serious consequences. The consequences of avionics systems failures, uncompensated by remedial action within the avionics systems themselves, in Categories III and IV systems, however, are likely to result in unsafe aircraft attitudes—with loss of flight path control or ultimate structural failure in the first category or, e.g., loss of aeroelastic stability followed by catastrophic structural failure in Category IV. None of these dire consequences will necessarily result from every failure or following failures in every application of avionics systems in Category III and IV systems. The point here is that the higher frequency response required of the avionics system to deal with the phenomenon of interest means that hard-over failures can occur too rapidly for a human pilot to counteract effectively.

It follows from consideration of the consequences of in-flight failures of avionics systems, such as given briefly in the preceding paragraph, that Categories III and IV systems must be redundant and have acceptable performance following a failure, either with partial authority, i.e., being capable of only part of the full control travel provided, or having switched the failed branch of the system off, i.e., making it inactive. A commonly used concept for identifying those parts of avionics systems with failures during flight operations

Table 1 Proposed categorization of avionics systems

Categories	Frequency response ω, Hz	Typical function	Redundancy required	Some aircraft using such systems
I	Not dynamic in their effect on aircraft behavior	Communications, navigation aids	Usually doubly or with alternatives	Almost all aircraft types
IA		Surveillance, target-tracking radars	None	AWACS, "Joint Stars"
II	$0 \leq \omega \approx 0.2$	Pitch trim through fuel usage, wing lift span distribution modification	None	Concord, C-5 (in development)
		Autopilots	None	Many aircraft types
III	$\approx 0.2 \leq \omega \leq \approx 2$	Roll, yaw damping	Doubly	CH-47, B-737,
		Stabilization (overcoming negative static margins), attitude- and load-limiting	Triply or quadruply	F-16, V-22
IV	$2 \leq \omega$	Buffet response reduction, higher harmonic rotor blade pitch control	Like Category III or greater	None as of 1998
		Increasing flutter speeds		F-16

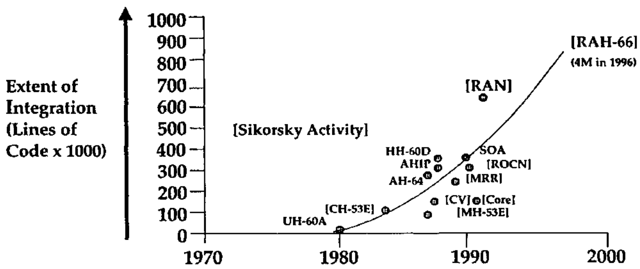


Fig. 3 Avionic systems integration perspective (from Ref. 2).

Table 2 Hierarchy classification (from Ref. 4)

Classification	Components	Redundancy levels
Flight critical	• Cockpit controls	Quad/triplex
	• PFCS software	"
	• Control surface actuators	"
	• Flight instruments	"
Flight phase essential	• AFCS software	Triplex/dual
	• AFCS sensors	"
	• MFDs[a]	"
Noncritical	• Autopilot	"
	• Flight director displays	Dual/single

[a]Multifunction displays.

is to have the processor compare output performance among three or more redundant systems and, when one deviates by more than a prescribed amount from the others, to switch it off. This is often known as "voting."

Considering the number of axes about and along which flight control may be required (pitch, roll, yaw; vertical, longitudinal, lateral) and the number of control mechanisms (elevators, ailerons/spoilers, rudders, engine thrust, thrust vectoring) along with redundancy and reliability requirements, the number of logical operations to be performed in components devoted to digital processing can grow to be substantial. In addition, system gains may have to be adjusted following a single system failure. Increasingly, avionics system processors are used for failure detection, isolation, and compensation through algorithms that compare how a system should be working, using real-time modeling, with how they actually are working. Some idea as to the growth of software is given in Fig. 3 (from Ref. 2). Experience with Category IV avionics systems is quite limited, as suggested by Table 1. Experience with Category III avionics systems, however, shows that the software that programs the digital processors may sometimes devote only 10% of its lines of code to performing the functions for which the avionics systems are intended; whereas the remaining 90% may be dedicated to failure mode alleviation and partial system operations. In terms of processor resources, such as time taken for a processor operation and memory allocations, the control laws portion can range from only 20 to 40% with the remainder being devoted to input-output, executive timing, self-test, and maintenance diagnostics.[3]

In a later part of this paper, it is noted that components of avionics systems often do double duty, in that they are integrated into more than one system so as to assist in performing more than one function. Thus, the same component might perform in a VMS function that is critical to safety of flight and also in a function that is not. The actuator moving a control surface force effector is an obvious example. This fact makes it important, in providing failure avoidance and amelioration, to categorize and often physically separate components in a hierarchical scheme, which is independent of the preceding categorization of systems. This is discussed in Ref. 4 and one such classification, along with redundancy consequences, is given in Table 2.

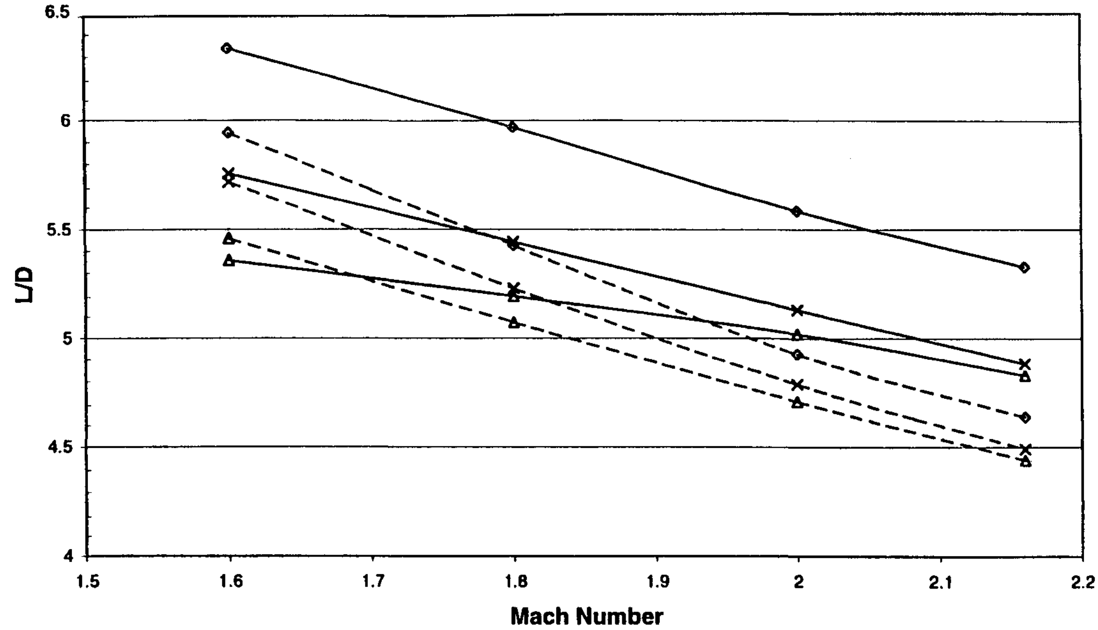
Some Examples of Avionics Applications Influencing Fundamental Aircraft Design Characteristics

Fundamental aircraft design characteristics in this context is intended to mean size, gross weight, and range (payload performance; i.e., such basic characteristics as are the focus of attention in conceptual and preliminary design stages). The avionics applications will be discussed in the order of and under categories proposed in the previous section. Because Categories I and IA generally have no significant influence in early aircraft design stages, by their very definition, the examples that follow are all in numerically higher categories.

Category II Examples

Payload-range performance in all aircraft types is influenced to some extent by trim drag in cruise flight, i.e., the increase in drag associated with the need to put moments into equilibrium. The extent of trim drag influence on payload-range performance depends on the aircraft configuration, of course, and tailless configurations are likely to be most affected by the need to trim pitching moments. Configurations with conventional tails have the relatively large lever arm provided by tail distance behind the aircraft CG to work with, so that relatively small changes in horizontal tail lift-force, with their relatively small associated changes in drag, can provide relatively large pitching moment changes. Tailless aircraft, however, usually must change wing camber to change aircraft pitching moments, with the associated relatively large change in airfoil section lift-to-drag ratios at constant lift shown in Fig. 4 (plotted from data given in Ref. 5 for a clipped delta wing without camber, NACA 64A004.5 before 40% chord, biconvex after 40% chord).

Primary requirements for changing control-generated pitching moments on aircraft can be the longitudinal shift in aircraft center of gravity that occurs as fuel is used and the large aerodynamic pitching moment changes that accompany transitions between subsonic and supersonic regimes. The former would certainly seem to be encountered by any swept wing aircraft with compartmented fuel tanks along the wing span. An interesting example of the latter had to be dealt with in the particular case of the Concorde supersonic transport aircraft. Accordingly, during its design, a system with components



Legend	C_L=0.2 Solid Line		C_L=0.3 Dotted Line	
	L.E. Flap	T.E. Flap	L.E. Flap	T.E. Flap
◇	0°	0°	0°	0°
×	10°	0°	10°	0°
Δ	0°	10°	0°	10°

Fig. 4 L/D vs Mach number for constant C_L (from Ref. 5).

sufficient to qualify it as avionics by the standards postulated in this paper was devised to ensure that fuel used from the aircraft's tanks would be in a sequence such that minimum longitudinal CG shifts occur, thereby minimizing trim drag. In fact, in some regimes, fuel is actually pumped from one tank to another.[6] Failure in this automatic fuel distribution usage system would result in the pilot having to take some remedial action, perhaps arranging for the sequence of fuel usage manually, flying at less desirable but more fuel efficient cruise speed, or even landing at an alternate airfield. So long as the pilot's displays were sufficient for him to be aware of the situation, however, the relatively slow rate at which these events unfold would allow time for corrective action. Such an avionics system for automatic fuel distribution usage would not, then, have to be redundant to ensure the high probability of reliable operation necessary when possible failures pose an immediate threat to flight safety. Nevertheless, the decision to employ this fuel distribution system ensuring reduced trim drag would have a direct influence on the size and gross weight of the aircraft designed for a particular range-payload performance.

A second example of a Category II avionics system is provided by a wing structure fatigue life extension arrangement used as an interim measure during the development of the Lockheed C-5A military transport airplane. The operational concept on which this automatic system was based followed from two physical laws, one aerodynamic, the other in mechanics of materials. First, a wing will have minimum drag induced by lift (induced drag) if the spanwise lift distribution is elliptic (e.g., Ref. 7). The C-5A wing in cruise flight, of course, was designed aerodynamically so that its spanwise lift distribution approached an elliptical distribution, to maximize range-payload performance, taking due account of the structural, i.e., weight consequences attendant on the bending and shear loading associated with such a spanwise distribution of lift. The second physical law is often expressed in so-called "Goodman Diagram" form; Fig. 5 (from, Ref. 8) shows that the lower the steady stresses in a material, the higher are the allowable alternating stresses for which the material will have infinite life—the so-called endurance limit. Because a major source of alternating stresses on airplane wings is gusts, i.e., atmospheric turbulence, in cruise flight, an automatic system was installed on the C-5A during its development phase that sensed the onset of turbulence (using, as sensors, accelerometers or wing bending strain gauges) and called for both ailerons, i.e., those on port and starboard wings, to retrim slightly upward when gust loads exceeded some level. This reduced the lift on the outboard wing sections. To preserve total lift, of course, the aircraft pitch attitude would be increased, but the total effect would be a spanwise lift distribution deviating from the approximately elliptical by having less load outboard, more inboard, and thus reduced steady wing root bending moments and associated steady stresses because of bending.

With this avionics system operative, the aircraft would have optimum cruise efficiency in smooth air, i.e., turbulence below some predetermined level, and lower aerodynamic efficiency when cruising in turbulent air. In turbulence, however, its wing root structural material would enjoy a more favorable position on the Goodman Diagram, so as to improve the wing structure's fatigue life. If such a system were found to be advantageous for an operational aircraft in the part of preliminary design concerned with wing structural weight, its designers could rely on lower combinations of steady and alternating stresses than would have existed if the more nearly elliptic spanwise lift distribution had been carried under all atmospheric conditions. As in the first example of Category II avionics systems, no quick-acting automatic actuation would be required for this spanwise lift distribution modification in rough air. However, because a flight path control component (ailerons) is involved, only limited authority would be given the actuators. Thus, if the system failed so as not to operate, the pilot could compensate by reducing airspeed, hence loads caused by turbulence, to levels of acceptable alternating stresses. If it failed with the ailerons in the up position, the pilot could take some of the range-affecting actions described in the first Category II example. In either case, however, appropriate pilot action would depend on having displays that reveal the existence and nature of the failure in this system. Again, as in the first Category II example, redundancy and a requirement for full or partial authority operation after a single failure would not be necessary

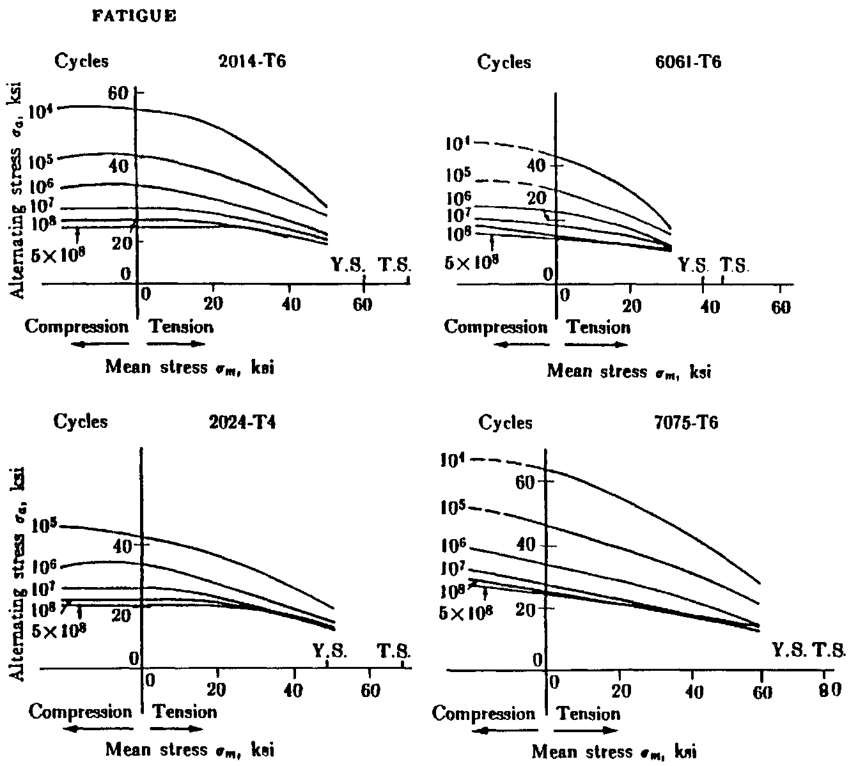


Fig. 5 Alternating stress vs time-mean stress as a function of life for several aluminum alloys (from Ref. 8).

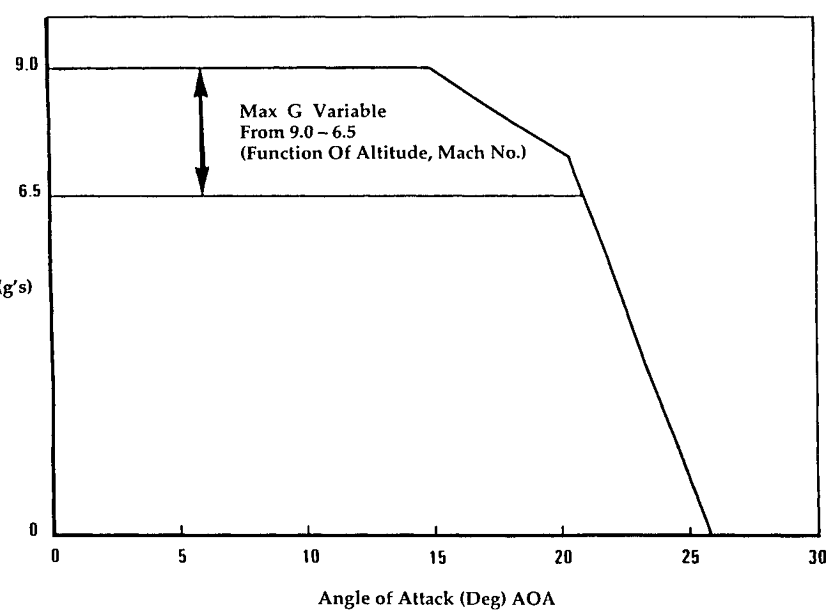


Fig. 6 Orginal YF-16 AOA g limiter concept.

for such an avionics system, which nonetheless could influence design of the aircraft at early stages. The final C-5A configuration, it should be noted, had a dynamic gust alleviation system of the kind discussed later under Category IV examples.

Another example of avionics systems usage falling into Category II is in maneuver load-limiting. The prototype of the F-16, the YF-16, was designed for a limit normal load factor of 9 times gravity, or $9g$, throughout most of its flight envelope, but as low as $6.5g$ in some critical areas. To prevent pilots from exceeding this limit, pilot commands were attenuated as a function of Mach number, altitude, and angle of attack (AOA). This system also limited AOA in an absolute sense, i.e., independent of Mach number and altitude. The associated automatic AOA/g (or N_z) limiting schedule is shown in Fig. 6 (from Ref. 9). The production version of the F-16 was designed with a $9g$ limit normal load factor throughout the operational envelope, eliminating the need for this particular avionics system, but AOA limiting was retained with variable limits as a function of roll rate as a means of insuring good handling qualities at extreme maneuver attitudes.

Category III Examples

It is widely accepted that the Wright brothers succeeded in flying powered, heavier-than-air machines where all others failed, mostly because they recognized the need for, and provided means of, roll control. They used wing warping, the predecessor to ailerons. One could hardly find a more convincing illustration of the overriding importance of effective means to provide equilibrium, stability, and control in an aircraft. Yet devices and arrangements for their provision are unquestionably detrimental to range-payload, maximum altitude, maximum speed, and other desirable aircraft performance

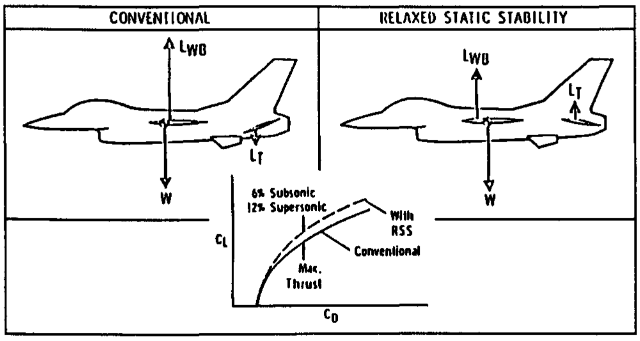


Fig. 7 Relaxed static stability results in smaller wing and less trim drag (from Ref. 9).

characteristics. Tail surfaces, for example, add weight and aerodynamic drag, and having the aircraft CG forward of the wing's center of lift (so-called positive static margin when the distance is in terms of average wing chord) as required for positive natural, i.e., unaugmented, stability in pitch, requires a download on the tail for equilibrium.

The present-day capabilities of avionics, with their high-frequency-capable actuators, allow designers to take advantage deliberately of the often superior range-payload, high-speed, and high-maneuverability performance of configurations whose unaugmented flying qualities are grossly unsatisfactory. Figure 7 (from Ref. 9) illustrates one of the advantages of reduced static stability (RSS) in pitch that were exploited in the basic design of the F-16 Falcon jet fighter. By integrating so-called RSS into the basic aircraft design, the horizontal tail was made to generate lift rather than download, so that the lift that the wing must produce is reduced. This means a smaller wing with less structural weight and drag can be designed. Further, for equal offsets of the wing's lift from the aircraft CG, either fore or aft, the tail lift (with RSS) can be less than the tail download (with positive static margin) so that the tail's drag, i.e., trim drag, will be less. The cumulative effect of these beneficial design changes, resulting from allowing an avionics SAS to compensate for RSS, is reduced fuel for the same range payload and a higher net thrust-to-weight ratio.[9] The latter is particularly important for fighter aircraft because it impacts maneuverability.

If the unaugmented flying qualities of an aircraft are sufficiently poor to constitute a risk to flight safety, however, the reliability of the SAS must be extremely high, e.g., approaching that of primary structure. Further, provision must be made to assure the kind of controllability that avoids hazardous aircraft attitudes and/or angular rates even in the unlikely event of hard-over system failures. In the case of the F-16, this resulted in a quadruply redundant stability augmentation system. Implications for the aircraft's design went beyond the fundamental range-payload and maneuverability mentioned before. As stated in Ref. 9,

> Since the pilot would not be able to control the aircraft in the pitch axis without the electrical system, there was no justification to retain a mechanical pitch system. The pilot's command could now be electrically combined with the stability system with no penalty. Removal of mechanical connection between pilot and the control surfaces was the logical result.

That is, making the SAS highly reliable and fail-safe allowed the use of an FBW flight control system with no mechanical backup.

The exploitation of avionics system capabilities to develop FBW flight control systems for subsonic commercial transport aircraft makes for an interesting comparison with those of fighters, an example of which was discussed in the preceding paragraphs. Stability augmentation is used in the Airbus 320 to improve aircraft flying qualities and allow download on the horizontal tail plane to be reduced—although not to the point of becoming positive lift—for the reduction in wing lift and drag that affords. To insure uniformity of the aircraft's response for a wide range of operating conditions, the flight control system has gains that are programmed as functions of airspeed, center of gravity location, and configuration of high lift component deployment. Further, however, control law features that prevent deviations from normal flight regimes sufficient to be dangerous are also incorporated. As discussed in Ref. 10, this aircraft's system introduces limitations of AOA at low speeds, to high-Mach-number operations, and to pitch attitude in combination with the first two so as to minimize accelerations. It follows that these flight envelope-limiting features mean, as in the preceding F-16 case, that control surface positions do not reflect the pilot's control inputs one for one.

As a consequence of the level of reliability needed, all possible failures in Category III system components must be accounted for in design stages and adverse consequences minimized. Multiple sensors and processors are provided in the Airbus transports for redundancy; in fact, five full authority digital computers control pitch, roll, and yaw. Moreover,

> each computer is divided into two physically separated channels; the first one, the control channel, is permanently monitored by the second one, the monitor channel. In the case of disagreement between control and monitor, the computer affected by the failure is passivated, while the computer with the next highest priority takes control.[10]

To prevent common mode failures, the designers of the systems described in Ref. 10 accepted the cost penalties associated with dissimilarity to provide two types of computers, namely: "two elevator and aileron computers (ELACs) and three spoiler and elevator computers (SECs) on the A320/A321, and three flight control primary computers (FCPCs) and two flight control secondary computers (FCSCs) on the A330/A340."

Compared to the late 1970s avionics flight control system on the Concorde,[6] which included mechanical backup for its FBW system on all three axes, the F-16 has none. The Airbus transports, however, have mechanical backup on a trimable horizontal stabilizer for pitch control and on the rudder. The latter control surface generates rolling moments sufficient that no mechanical backup is provided for ailerons.

The emphasis on safety resulting from the sober responsibility of carrying hundreds of passengers is certainly understandable. In addition, however, competition among airlines to win the business of these passengers motivates commercial transport airplane designers to take advantage of FBW systems and avionics system components capabilities to do double duty. One such application is in enhancing passenger comfort in turbulent air. As seen in Fig. 8 (from Ref. 10), there are significant frequency components in atmospheric turbulence that place systems designed to ameliorate those effects beyond 2 Hz, and hence beyond what has been defined as Category III. In fact, on the Airbus A340 aircraft, response to turbulence of the sort to affect passenger comfort is composed of both rigid body and structural dynamics. The double-duty aspects, which—as mentioned earlier—can be thought of as integrating multiple function flight control systems, are important enough to be dealt with in a separate section of this paper.

Before moving beyond Category III systems examples, however, two more from the world of rotary wing aircraft are worth mentioning: an advanced scout-reconnaissance helicopter and a tilt rotor vertical takeoff and landing (VTOL) aircraft. A helicopter's ability to hover is virtually its raison d'être. Hover, as a flight regime, however, has only limited utility except near the ground. It follows that, in addition to the aerodynamic reference system of prime importance to all aircraft, helicopters will also benefit from reference to axes fixed in the Earth, to be used in hover flight regimes. In addition, the rotor's ability to provide vertical accelerating forces (thrust) in still air is one more control effector not available on most fixed-wing, conventional takeoff and landing aircraft. Some indication of the additional complexity and sophistication required of helicopter avionics systems designed for autopilot and SAS functions, compared to fixed-wing aircraft, is provided by Table 3, from Ref. 11. This table shows the kinds of sensors and processing required to generate the response to pilot commands and stability characteristics desired for the RAH-66 Commanche helicopter.

How tilt rotor VTOL aircraft work is, by now, quite widely known. Still it is useful in the context of this paper to see the control effectors available to make flight control of this versatile aircraft type commensurately versatile. Figure 9 (also from Ref. 11) presents

Table 3 RAH-66 Comanche command response/stabilization characteristics (from Ref. 11)

Characteristic	RAH-66 command response/stabilization: Core AFCS		Selectable AFCS (velocity stab/alt hold)		
Axis	Hover and low speed	High-speed forward flight	Hover	Low speed	High-speed forward flight
Longitudinal	Rate/attitude		Velocity command/ position hold	Attitude command/ attitude hold	Attitude command/ airspeed hold
Lateral	Rate/attitude		Velocity command/ position hold	Attitude command/ attitude hold	Rate command/ attitude hold
Directional	Rate/heading	Rate/heading with automatic turn coordination	Rate command/ heading hold	Rate command/ heading hold with autoturn coordination based on groundspeed	Rate command/ heading hold with autoturn coordination
Vertical	Rate of climb		Rate of climb	Rate of climb/altitude	

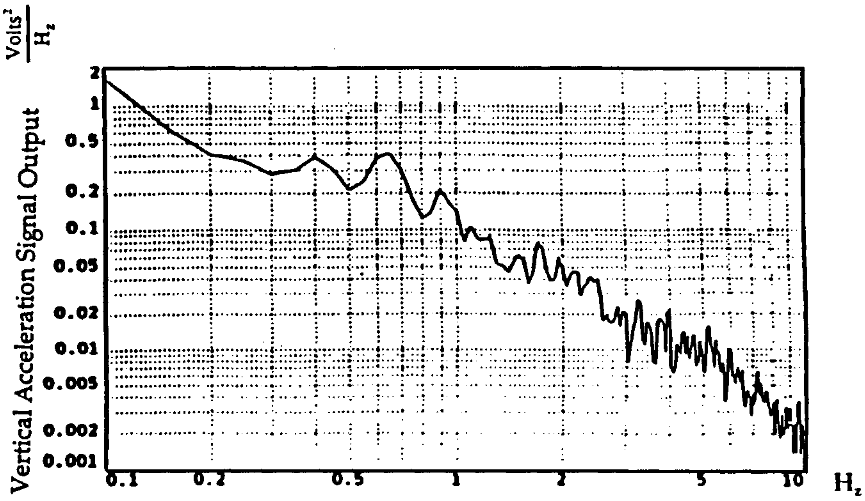


Fig. 8 Gust frequency spectrum (from Ref. 10).

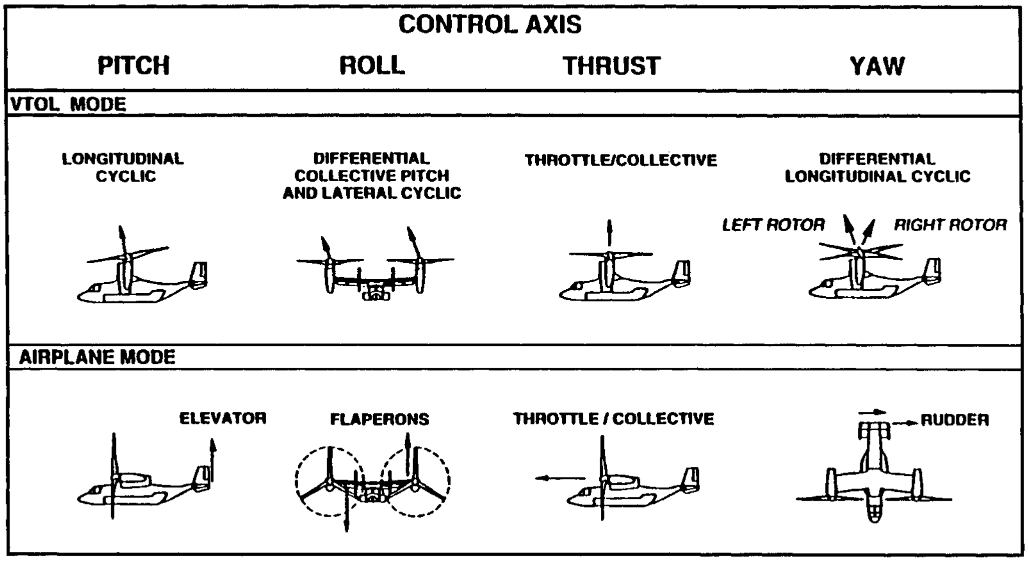


Fig. 9 V-22 flight control configuration (from Ref. 11).

this information for the V-22 Osprey tilt rotor aircraft, for both the VTOL (helicopter flight) mode and the fixed-wing airplane regime. What is not shown, but is easily understood, is that effective control must be available to the pilot at every point in the transition from one flight mode to the other. Further, only one set of pilot input controls is acceptable for all this; it would clearly be unsatisfactory for the pilot to have to abandon one set and pick up another at some point in this transition. To the sets of sensors customarily used in avionics flight control systems, nacelle, i.e., rotor, tilt relative to aircraft reference axes becomes, for tilt rotor aircraft, an important and readily available addition. Rotor-driven VTOL configurations, which have flown more or less successfully, include the VZ-2, CL-84, and XC-142A (tilt wing aircraft) and the XV-3 and XV-15 (tilt rotor aircraft). However, among the many technological advances making these configurations more susceptible to practical implementation, the advent of avionics capable of being adapted to effective VMSs must be counted among the most important. Consider the complexity of mechanical systems for mixing and phasing in and out control effectors for VTOL vs airplane flight modes in Fig. 9, compared to the relative ease with which that can be done in a digital processor.

In the case of single lifting-rotor helicopters with horizontal tail surfaces (as most have), with tandem rotor helicopters, and with tilt rotor VTOL aircraft, it will be noted that there is aerodynamic redundancy in how pitching moment equilibrium—more frequently called longitudinal trim—is achieved. It is often attractive to use this redundancy to reduce stress levels in primary structure. Rotors are a part of primary structure particularly subject to high cycle fatigue in both helicopters and tilt rotor VTOL aircraft. These facts lead to use of rotor blade flapping angle or blade root bending (out of the plane of rotation) stresses as still another sensed signal usable in avionics primary flight control systems, as discussed in Ref. 11.

Category IV Examples

Structural problems of a dynamic and/or aeroelastic nature are usually thought of as falling into either self-excited or forced vibratory classes. Flutter of wings and tail surfaces, the latter usually coupled with aft fuselage motion, and both sometimes coupled with control surface deflections, is in the self-excited, i.e., aeroelastic, stability class. So are the whirl-flutter and coupled rotor-wing phenomena that can be thought of as including mechanical instabilities, such as helicopter so-called ground resonance (a misnomer), as a subcase. Pilot-induced or pilot-assisted oscillations are briefly described later and won't be mentioned further in this section. Within the class of forced vibrations are gust response (discussed earlier in this paper), rotor-excited vibrations in rotorcraft, aeroacoustics, and tail buffet. All of these phenomena involve motions whose basic, i.e., natural, frequencies are usually well beyond 2 Hz, so that if avionics systems are incorporated for their control or amelioration, they would fall into Category IV.

Virtually all of the phenomena for which Category IV systems are intended must be considered with such Category III systems as SAS, active, if such exist, because of their possible effect on the unaugmented aircraft's structural dynamic and/or aeroelastic behavior. It is noted, e.g., in Ref. 1, that when a "stable aeroelastic mode is destabilized by the control system, this is called 'spillover.'" Aeroelastic stability (and flight path stability, for that matter) must, therefore, be assured with all systems functioning in all possible modes of operation, including partial failures. Active modification of structural and/or aeroelastic phenomena by means of avionics systems may, in any event, be thought of as acting by virtue of either reducing the (usually aerodynamic) forcing functions, generating directly opposing forces, or by introducing stiffness changes and/or additional damping into the motions crucial to the instability.

In a far-sighted series of research programs, the U.S. Air Force investigated the use of flight controls to reduce airframe design criteria as concern structural dynamics more than 20 years ago. One such project was the load alleviation and mode stabilization (LAMS) system, and the entire conceptual approach was known as CCV (control configured vehicles). As stated in Ref. 12, "On Aug. 2, 1973 aviation history was made in the skies over western Kansas when the CCV B-52 test aircraft was flown 10 knots faster than its flutter speed." The flutter mode control (FMC) system used in that program had vertical accelerometers in pairs at four locations on the wing to produce signals that, processed by shaping filters, drove outboard ailerons in one independent loop, sensors to surfaces, and outboard flaperons, in a second. The system was predicted to increase flutter placard speed by more than 30% by increasing damping in and improving coupling between the structural modes active in the aeroelastic instability. This LAMS demonstration program was well conceived and the B-52 well chosen for it. The normally stable aeroelastic modes could be made unstable within the aircraft's normal speed range by placing lead weights far forward in auxiliary wing fuel tanks. Because the mode dominant during flutter, involving wing and body, had a relatively low frequency (2.2–2.4 Hz) depending on gross weight, and the flutter onset was predicted and later verified to be mild, the concept could be proven without undue demand on the avionics and with relative safety.

As regards the latter point, Fig. 10, from Ref. 12, shows that wing failure would have occurred only after about 35 s of unconstrained

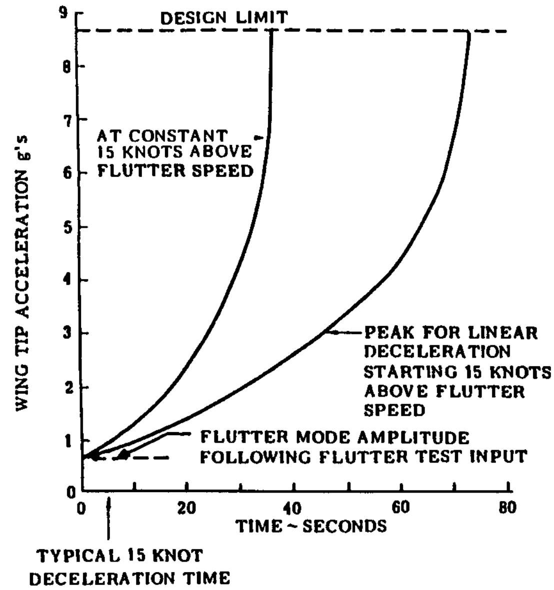


Fig. 10 Wing tip acceleration after total FMC disengage (from Ref. 12).

flutter amplitude growth, following a purposeful flutter test input excitation at 15 kn (not 10 kn) above the uncontrolled (avionics system inoperative) flutter speed. Further, it would take more than 70 s to fail the wing if the aircraft were to decelerate linearly, whereas deceleration by 15 kn could be achieved in about 5 s. To achieve the benefit of lower wing structural weight through use of avionics to stabilize otherwise unstable flutter modes on aircraft with higher frequency flutter-dominant vibratory modes than the B-52 has with wing-mounted tanks, however, would require systems with higher bandpass capability. Further, the reliability and redundancy—only dual for ailerons and dual for flaperons in the Ref. 12 tests—would have to be considerably higher for flutter phenomena that are more explosive than mild.

Figure 11 shows the theoretical structural damping vs airspeed required to cause combinations of vibratory structural modes to become aeroelastically unstable. The points for a B-52 were taken from Ref. 12; the second curve is hypothetical, but not unreasonable. The slope of required damping vs speed is one indicator of the mildness or explosiveness of the aeroelastic phenomenon and, generally, the steeper the slope, the more rapidly divergent the flutter oscillatory amplitudes. If the times to reach design limit in Fig. 10 are reduced to fractions of a second, as is more likely than not for many aircraft, Category IV avionics systems put to FMC use must, clearly, have the same level of reliability as the airframe primary structure itself, a point made earlier, referring to Category III systems such as SAS.

In roughly the same period as the Air Force CCV R&D activities, NASA's Aircraft Energy Efficiency program was inspiring increased wing aspect ratios of magnitude sufficient to make consideration of avionics systems for maneuver load control, elastic mode suppression, and gust load alleviation (GLA) seem advisable for commercial transport aircraft. Related to the Aircraft Energy Efficiency program, therefore, was the development and flight test of an avionics flutter margin augmentation system suitable for the L-1011 jet transport by Lockheed.[13] In this application, the first symmetric wing bending modes with frequencies of 1.3–1.8 Hz, depending on wing-carried fuel, and a wing-engine pitch/torsion mode with a natural frequency of 2.75 Hz, all at zero airspeed, were dominant in the flutter. The force effectors used were ailerons and the all-flying horizontal tailplane; sensors were accelerometers indicating wing tip vertical, engine vertical, i.e., pitching, and engine lateral accelerations. Three flutter margin augmentation schemes were evaluated: ailerons driven by wing tip vertical accelerations, ailerons driven by engine vertical and/or lateral accelerations, and horizontal stabilizer driven by engine vertical and/or lateral accelerations. Although basic aircraft aileron response was adequate for these purposes, the all-flying tail surface required a hydraulic actuator valve change and raising hydraulics operating pressure from 7.0

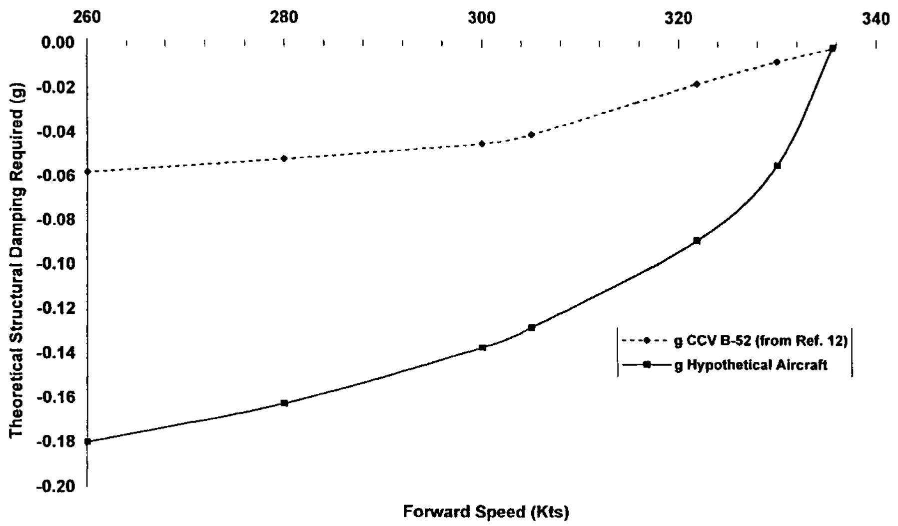


Fig. 11 Structural damping required for neutral aeroelastic stability (flutter speed).

to 10 MPa (1000–1500 psi) to double the servorate limit from 50 to 100 mm/s (2–4 in./s). Flight tests of these alternative systems consisted of flying at speeds within the stable envelope and measuring the rates of decay of motion, following oscillatory excitation. The results showed that the system with aileron driven by engine lateral acceleration produced no modal damping increase. The other system combinations increased modal damping by amounts between 118% and zero.

As in other areas of avionics systems applications, flutter suppression can be expected to gain increasing effectiveness through application of microprocessor developments and modern methods of designing control systems. Aircraft with varying payloads and/or external stores configurations are seen by automatic control systems as having uncertain characteristics. Aircraft flying at various altitudes, speeds, and fuel loads are also seen as plants with changing parameters. Adaptive controllers with real-time system identification processes, therefore, have substantial promise for FMC. Numerical simulations of such advanced FMC systems were reported in Ref. 14, considering a simple cantilevered, unswept, semispan rectangular wing with effective full-span aspect ratio of 7, flexible in bending and torsion and having a flutter speed of 38 m/s (125 ft/s) and flutter frequency of 11.72 Hz, without feedback, in a mode that was predominantly a combination of first bending and first torsion modes in still air. Force effectors whose effectiveness was examined in the FMCs included various numbers of rigid control flaps on the trailing edges of the wing. The most effective arrangement consisted of four flaps, each of 10% semispan at the outermost span location driven by a four-channel least-mean-squares algorithm. The control spring on these flaps provided an uncoupled rotational frequency of 60 Hz. The motions sensed in this system were wing pitch angle at those wing sections where control flaps existed; i.e., the sensors and control effectors were all nearly collocated. Stable operation 63% above the basic wing's flutter speed was achieved using this FMC. The controller could accommodate disturbances (generated by the outermost flap) every 3 s, and rapid airspeed changes, up to 2.7 m/s^2 (9 ft/s^2), did not defeat the system—which because of its basic, system identification premise, needed no prior information about the wing it stabilized. Although Ref. 14 did not consider the hardware aspects of implementing such a system on an actual aircraft, it does seem to portend the future for aircraft whose designs can benefit from FMC systems.

Forced structural dynamic response of airframe components has many sources of excitation, and a tremendous literature, of course, exists on the subject. Some of these excitation sources are 1) gusts, i.e., atmospheric turbulence, 2) aircraft wake induced turbulence [both tail buffet (boundary-layer separation) and trailing vortices from rotor/propellers], 3) engine and rotor/propeller hub forces and moments, 4) rotor/propeller blade tip proximate passage, 5) gear box mount transmission at tooth contact frequencies, and 6) rapid fire weapon recoil and/or muzzle pressures. Gust loads have been discussed earlier in this paper, but not in terms of systems whose dynamics, i.e., bandpass capability, are sufficient to counter gust excitation (with significant components at frequencies up to about 7 Hz) as it occurs. Such would be Category IV systems, and an example is cited in Ref. 1. In that case, the Air Force C-141 "Starlifter" jet transport was found to have sufficient wing response to gusts that significant metal fatigue was being incurred after a few hundred hours of flight. An avionics system driving ailerons and based on wing accelerations so as to add aerodynamic damping to the lightly damped, offending aeroelastic modes was used to cure the problem. A similar approach was used during the development of the Lockheed trijet transport, the L-1011, and the performance of its load alleviation system was a substantive part of the FAA's certification of the structural integrity of the version of that aircraft actually put into service.

As would be expected, development of avionics systems applied to GLA have continued. Reference 15 describes the results of such research using a $\frac{1}{9}$-scale semispan, cantilever model of a wing with aspect ratio of 10.5, taper ratio of 0.3, and quarter chord sweep angle of 18 deg. Various combinations of ailerons at two different span locations, a leading-edge control surface, accelerometers and strain gauges in the wing span, as shown in Fig. 12 from Ref. 15, were considered. When the leading-edge surface was driven simultaneously with ailerons, a second separate DC motor and potentiometer were used, but such combined force effectors weren't applied to GLA systems. Oscillating vanes upstream of the wind-tunnel test section allowed both sinusoidal and continuous spectrum, atmospheric-type turbulence to be simulated. The relatively small differences in spanwise aileron location made little overall difference to GLA system performance, one reducing second mode response better than first mode and the other vice versa. Ailerons alone were found more effective in GLA in these tests than leading-edge surfaces alone. The kind of reduction in response to atmospheric-type turbulence possible with a system with both accelerometer and strain gauge sensors (called Control Law 2) to drive an aileron is shown in Fig. 13 (also from Ref. 15.)

The excitation caused by either atmospheric turbulence or buffet because of boundary-layer separation have in common broad spectra, i.e., a fairly broad range of frequencies at high amplitude. Systems intended to reduce the response to such excitation, therefore, are ineffective when they attempt to change modal frequencies. Systems optimized in developments such as those reported in Refs. 1 and 15 turn out to be simply adding damping to the existing responsive modes. When trailing vortices from rotor/propeller blades are the source of excitation, however, the spectra has sharp peaks at the blade passage frequencies. Vortices generated purposefully for increased maneuverability in fighters also produce spectral peaks and are discussed in the "Advent and Impact of Smart

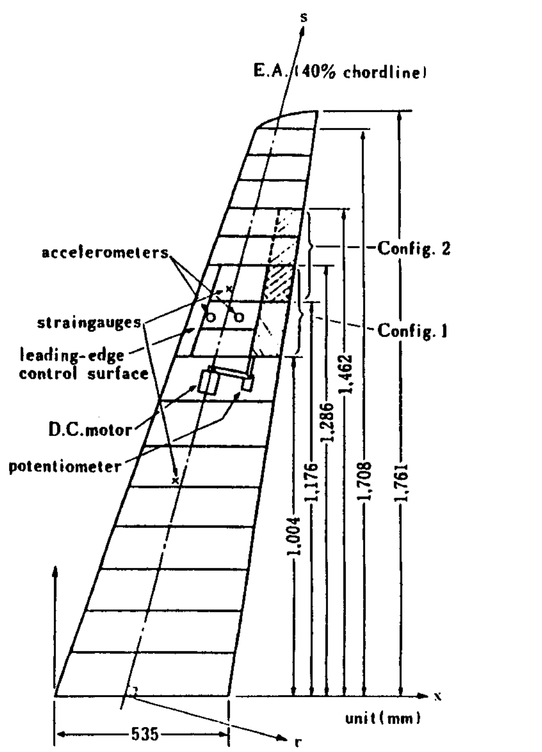


Fig. 12 Wing model with the actuator for configurations 1 and 2 (from Ref. 15).

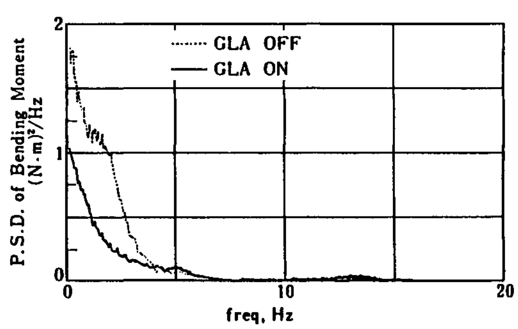


Fig. 13 Power spectral densities of bending moment because of continuous turbulence with GLA system (Law 2) on and off.

Materials/Structures" section. In such cases where blade passage or concentrated vortex frequencies are close to resonant with a structural dynamic mode, then an optimum avionics system might be quite effective if it changed natural frequencies using aerodynamic forces or, as mentioned later, smart materials for the purposes of load alleviation or comfort improvement, or both.

Rotating machinery and rotor/propellers have been sources of forced vibration, with undesirable associated structural loads in airframes and pilot/crew/passenger discomfort, since the advent of powered flight. Rapid fire weapons cause similar problems because of recoil and muzzle pressures on military aircraft. Shock and vibration mounts and dynamic absorbers often, at the points where these components mount to the airframe, have been used to reduce the undesirable effects of these loads. These are usually passive devices, in the sense that they require no power input, using the energy associated with the offending dynamic component, and/or its vibratory motion, to generate the desired ameliorating inertia forces. Because dynamic absorbers in their various forms are almost always resonant devices, it is sometimes necessary to vary their natural frequencies so that they can function effectively when the rotational speed of the turbomachinery or rotor/propeller changes even slightly. Thus, some dynamic devices are semi-active in the sense that an avionics system is used to vary their parameters so as to always be most effective, regardless of changes in excitation frequency.

In rotorcraft it has become almost equally commonplace to consider installing generators of opposing vibratory forces in an active

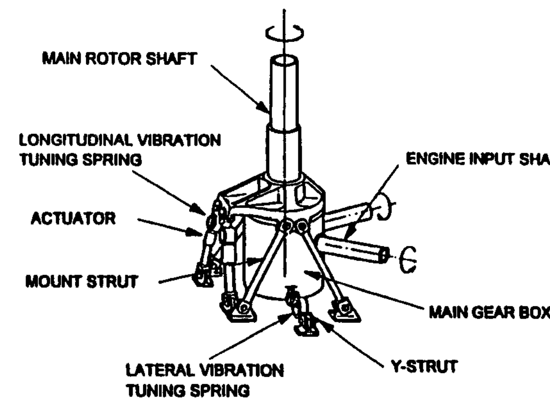


Fig. 14 Typical AVR system application (from Ref. 16).

mode. Such devices often have near-resonant spring-mass components to reduce force and power input requirements, but they are driven by powered force effectors such as high bandpass-capable hydraulic actuators on the basis of signals from sensors 1) at positions in the aircraft, 2) at frequencies, and 3) in the direction in which reductions in vibratory amplitudes (or, presumably, stresses) are desired. Reference 16 describes such an active vibration reduction (AVR) system installed at the points where the main rotor of the BK-117 helicopter is mounted to the fuselage, as shown in Fig. 14 from that reference. This AVR system is controlled on the basis of signals from a combination of sensors in the cabin and cockpit.

A concept that makes use of avionics systems to reduce the generation of rotor/propeller vibratory forces still closer to their source is known as higher harmonic control (HHC). Based on signals, once again, from sensors where vibrations and their particular characteristics are to be improved, actuators apply dynamic changes in rotor blade geometric pitch angle as the blades rotate, i.e., during each rotation. Wind-tunnel test results for such systems and their control aspects are discussed in Ref. 17, and results obtained in helicopter flight tests in Ref. 18. Although promising, no application of higher harmonic control has yet appeared on a rotorcraft in service operations.

It is worth noting that tilt rotor VTOL aircraft are subject, in cruise flight, to rotor-induced vibrations associated with passage of rotor blades through the variable flowfield caused by the wing that is behind only the inboard portion of the rotor discs. Reference 19 describes a system of HHC and flaperon actuation driven by a combination of signals from accelerometers on the wing tip-mounted engine nacelles and bending and torsion gauges on the inboard wing spar, as shown in Figs. 15a and 15b from that reference. Wind-tunnel model test results indicated that the HHC system can reduce both the blade passage and one per revolution frequency response (the two major sources) by 55–75%, using pitch angle and flaperon oscillation angles of about 1 and $\frac{1}{2}$ deg, respectively. Further, the system tested was extremely robust with respect to rapid changes in rotor speed and/or airspeed, and gain-scheduling was almost as effective as an adaptive algorithm, but only produced a slight advantage in terms of computing time.

The preceding paragraphs suggest that one would be safe in assuming that some Category IV systems are flying on aircraft in service, and influencing either the allowable operational lifetimes or weight of the primary structures or both, whereas others have been validated in experimental flight tests, but have not yet influenced operational aircraft design. Gust alleviation and vibration reduction systems are included among the former systems; flutter and other aeroelastic and aeromechanical instability suppression, for the most part, are among the latter. In some aircraft designs, certain structural characteristics must be stiffened to push structural dynamic and/or aeroelastic instabilities beyond the operational flight envelope, and this often helps to determine structural weight. In those cases, relying on instability-suppressing avionics systems could allow structural weight to be reduced, allow thinner airfoil sections to be chosen, or otherwise improve the performance of the aircraft, particularly if adopted in early design stages. If the associated systems can, in fact, be made to have the same kind of reliability as

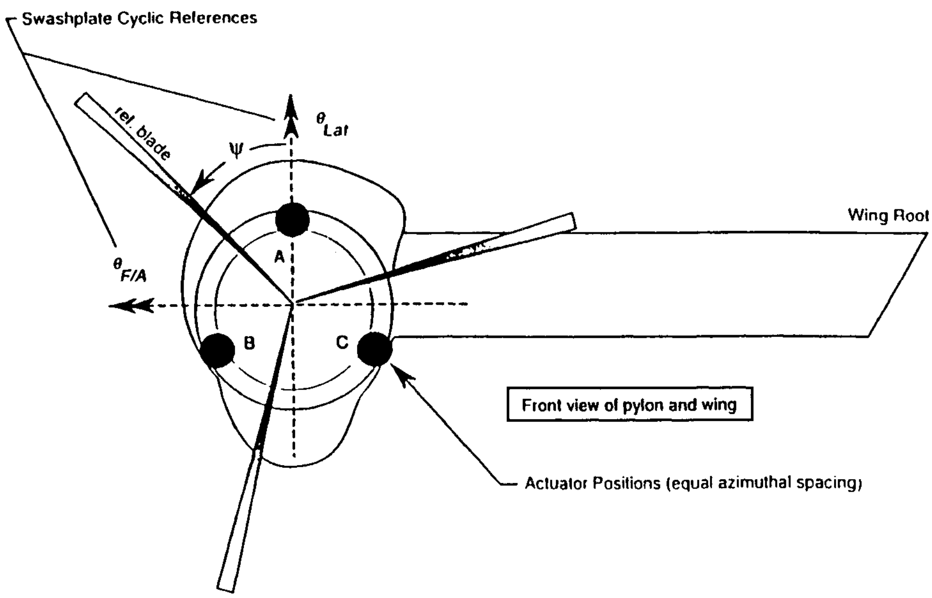


Fig. 15a Actuator positions and swashplate cyclic reference (from Ref. 19).

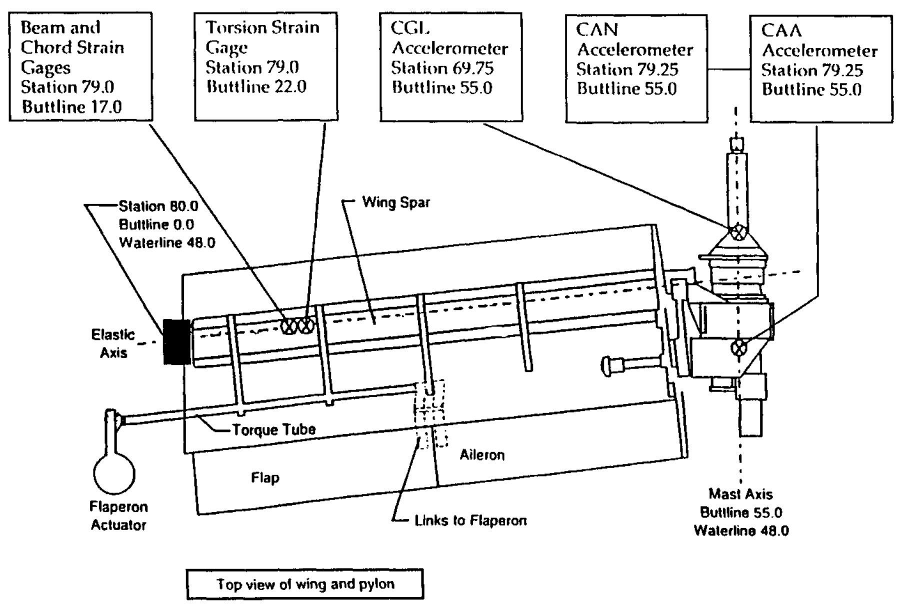


Fig. 15b Wing planform geometry and location of gauges used for response feedback (from Ref. 19).

primary structure, taking advantage of that potential seems a logical next step in avionics integration in aeronautics.

It is noteworthy that researchers in this field, often called aeroservoelasticity, have envisioned and investigated integrating "active controls with a highly flexible, advanced aerodynamic wing design to produce enhanced aerodynamic performance and control."[20] Providing the kind of flexibility that would allow a wing to take on variable twist and, perhaps, camber so as to be close to optimum for a range of flight conditions would be expected to lower critical flutter speeds, unless the active system would also function in a flutter suppression mode. Wind-tunnel tests were, therefore, conducted in this project (the Active Flexible Wing Program) on models of such a concept, using various combinations of accelerators and strain gauges, inboard and outboard trailing-edge flaps, and two kinds of control laws: one for rolling maneuvers, the other for flutter suppression. The test results were reported in Ref. 21. This research demonstrated high-rate rolling maneuvers at dynamic pressures 11–17% above the uncontrolled flutter boundary.

Integration of Functions in Avionics Systems

The tremendous capabilities of digital processors, for low weight and cost in a small volume, makes it obvious that many of the functions desired of avionics systems, regardless of the category defined earlier, can all be handled in one processor. Further, it is clear that a given control effector can generate forces or moments for more than one purpose, so long as their actuators have sufficient frequency response. Thus, certain avionics system components can do double duty. It follows that advantages would seem to come with integrating as many aspects of flight path control, navigation, stability, engine control, mission performance, and load reduction as possible in the design stage.

Combining structural mode control to reduce response to turbulence and improve passenger comfort with SAS functions is an example of such functional integration. The same vertical accelerometer used in implementing the A320's longitudinal flight path control law, for example, was used in the normal acceleration turbulence damping function.[10] Further, no additional control surface or actuator was needed over that used for flight path control. Because three coupled structural/rigid body modes were the principal contributors to gust response on this aircraft, three commands—one vertical/longitudinal and two lateral/roll (fuselage torsion)—were generated to increase effectively the damping in these structural modes. The first produced elevator commands; the last two were directed to the rudder. Figure 16 (from Ref. 10) shows how the

Table 4 Available control effectors (from Ref. 22)

Effector	Pitch	Roll	Yaw	X-Force	Y-Force	Z-Force
Stabilators	√	√				
Canards	√		√		√	√
Ailerons		√				√
Flaperons		√				√
Rudders			√		√	
Gross thrust				√		
Vectoring	√	√				
Reverser vanes	√	√	√	√		
Main gear			√	√		
Nose gear			√			

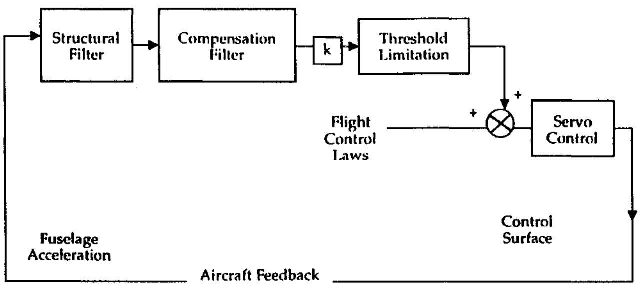


Fig. 16 Turbulence damping: principle of one lane (from Ref. 10).

structural mode response commands were generated; this is typical of the systems used for all three modes. Note that, although Fig. 8 shows that this additional, comfort improvement function for elevator and rudder controls takes the frequency requirements beyond the Category III range (≥2 Hz), improving passenger comfort is not a safety of flight issue. Hence, if limited authority is used in these channels, the level of reliability/redundancy needn't be as high as for Category III flight path control (SAS) functions. Such would not be the case, however, if structural mode control had been intended, instead of comfort, for reducing wing fatigue stresses by dynamic, i.e., alternating stress reduction. This kind of avionics systems integration, if exploited during early design stages for the A320, could have been used to lower wing weights in the parts of its structures where fatigue caused by turbulence is the critical design condition, as was done in the design of the Lockheed L-1011 trijet transport mentioned earlier.

Some advanced military aircraft concepts are making the integration of VMS functions increasingly necessary. Reference 22, for example, reviews a U.S. Air Force program to "develop and validate through analysis, experiment and flight test" configurations integrating technologies that would make high performance fighters capable of both short takeoff and landing (STOL) and enhanced combat effectiveness. To be considered in that study were aerodynamic control surfaces, including all-moving canards, engine thrust magnitude variation and vectoring, and landing gear steering and braking. Table 4 lists these control effectors. The first five are aerodynamic surfaces, the next three are engine controls, and the last two deal with the landing gear. For thrust vectoring to provide roll control, a multiengine configuration with lateral separation is required. In such a configuration, if gross thrust variation is available for X-force control at reasonable frequencies, differential gross thrust might also be available for yaw control. Spoilers might also be useable for yaw and roll control and X-force in a speed-brake mode of operation.

The fact that landing gear steering and braking are included in a listing of control effectors to be considered in designing integrated flight and propulsion control systems for a fighter with STOL capabilities emphasizes that modern avionics used for VMS functions must be made capable of functioning effectively in a wide variety of flight regimes and modes of operation. Of course, the pilot should not have to vary his flight path command behavior as the changes that accompany passage from a short takeoff run to being in free flight take place. It may be desirable to have some control law moding selectable by the pilot, say for programmed evasive maneuvers in combat or for perceived threat counteraction. Such optimized capabilities can be integrated as mission-related pilot-selectable functions using the same flight control, engine, and fire control systems that exist for other purposes. On the other hand, switching from one mode of operation to another, in most cases, should be simply a result of 1) the pilot control command inputs that are natural and essential to the task and 2) the output from applicable sensors—e.g., in the STOL short-landing maneuver, by signals generated by force on the landing gear or shock absorber (oleo) extension.

Another, rather unusual, integration of landing gear control effectors into flight control systems is to use an extending nose gear strut to rotate the aircraft for takeoff, as is done on the Lockheed Martin/Boeing "Darkstar" reconnaissance drone. The moment arm between the elevons and the main landing gear "is so short" on this tailless design "that it is very difficult to rotate the aircraft on the ground."[23]

Automated operating-mode switching might be part of avionics systems adaptations designed to accommodate configuration changes such as those that exist on a transitioning tilt rotor aircraft, as noted earlier, or according to flight regime. An example of the latter would be a fighter that only uses maneuvering flaps and/or leading-edge slots at high AOA. Most of such switching should be transparent to the pilot. Another example is provided by those flight control functions limiting loads to acceptable values, so as to provide the pilot carefree maneuvering. Yet the pilot should not be confused or puzzled by the aircraft suddenly becoming unresponsive to command input or behaving unexpectedly in other ways. Thus, appropriate cockpit displays are an essential part of flight control systems that are multimodal and multifunctional. Increasing the number of automated mission-related functions—such as navigation, low altitude terrain avoidance, and for helicopters, external (sling) load lifting—that are served by automatic flight control, propulsion, and fire control systems relieves the pilot of those responsibilities and increases the amount of time a military pilot has available to think tactically. This aspect of integrating elements of flight control systems is discussed in Refs. 11 and 24 including, in the latter, the need to ensure the pilot's situational awareness through easily assimilated displays.

Integrating flight control system elements for multiple functions and mode switching, however, is not limited to aircraft designed for military missions. In the operation of commercial, multiengine jet transport aircraft, loss of the primary flight control system is a rare, but possible occurrence. Examples include a United Airlines DC-10 in Sioux City, Iowa, a Japan Airlines B-747 over Japan, and a Turkish DC-10 over Paris. Another such incident with a Delta Airlines L-1011 in Los Angeles did not become an accident only because of exceptional skill on the part of the crew. Recommendations from the National Transportation Safety Board led to research into the development of propulsion-controlled aircraft. In this concept, inoperative primary flight control systems (because of nonfunctioning aerodynamic control surfaces, their actuators, and/or avionics system linkages) are replaced to the extent possible by engine throttles acting in parallel so as to provide pitch and/or fore and aft controls for climb and descent, and acting asymmetrically to control yaw and bank angle.[25,26] This would seem to be a case where mode switching, using multifunction integrated avionics system elements, should be automatic and the pilot made unmistakably aware of the situation.

It is useful, particularly in view of the integration of avionics components into more than one functional system, to think of these systems as being of the kind that 1) change the behavior of the uncommanded airframe, which might be called Function 1; 2) change the behavior of the uncommanded engines, Function 2; 3) modify the pilot's command signals, Function 3; 4) provide mission-related command signals themselves, in the manner of a pilot's associate, Function 4; and 5) provide mission-enabling information to the pilot, Function 5. The last of these is a function that allows the pilot to fly where he/she wants to go and how he/she wants to get there—in the case of general aviation, commercial, and military transport aircraft. In the case of combat aircraft, Function 5-type equipment can really be considered part of the payload because finding the enemy and/or neutralizing the enemy may be the fundamental reason(s) the mission is undertaken in the first place. These broad functional categories are listed as follows:

1) changing behavior of uncommanded airframes
   a) flight path stability augmentation (SAS)
   b) aeroelastic instability suppression (FMC)
   c) load reduction
2) changing behavior of uncommanded engines
   a) compressor stall avoidance
   b) emission amelioration
   c) noise reduction
   d) improving combustion efficiency
3) acting as pilot's associate
   a) threat avoidance maneuvers
   b) target tracking/weapon pointing
   c) formation flying/station keeping
   d) automated landings
4) providing mission enabling pilot information
   a) communication
   b) navigation
   c) collision/terrain avoidance
   d) target/threat location.

What we have defined as Category I systems are usually Function 5; Category II systems are, for the most part, Function 4; and Categories III and IV carry out tasks whose natures are as Functions 1 and 2. From the automatic controls viewpoint, Category I systems (Function 5) require and involve no feedback; Category II systems use feedback in Function 4, but in the outer loop; and Categories III and IV have feedback and contribute to constituting the inner loop in Functions 1 and 2.

Here it is noted that, although engine performance can be and sometimes is essential to automatic flight control system effectiveness, control of the engine itself is usually delegated to components that are not integrated with other avionics systems. Among the reasons for this separation are the need to test engines, including their control systems, as a unit before installation in an aircraft; the uniqueness of some of the sensors required (fuel flow, turbine RPM, turbine inlet temperatures); and minimizing "linkage" distances. This is shown, graphically, in Fig. 17 for an advanced helicopter. Using this diagram as an example, the MEP are seen as performing Function 5. The engine control unit (particular types of which are known as full authority digital engine control), the automatic flight control system (AFCS, containing SAS), and the primary flight control system (PFCS) perform Functions 1 and 2. The Category II, Functions 4 are not shown. Neither is the integration of engine control into load minimization control loops taking drive shaft flexibility into account in rotorcraft, although such is discussed rather thoroughly in Ref. 11.

Avionics systems techniques are also being developed that could be integrated into turbine engine controls to allow turbomachinery performance increases and reductions of elements in their exhaust harmful to the environment. Turbine engine performance generally improves the closer their operations are taken to compressor stall. Yet stall in service operation is unacceptable. Feedback control has been shown to be capable of extending the effective stable flow range of axial compressors and rejecting persistent disturbances that otherwise would cause the system to incur rotating stall. Reference 27, for example, demonstrated such improvements in experiments with a low-speed, single-stage axial compressor using static pressure sensors in the inlet duct to control a low inertia butterfly valve that adjusted pressure in a plenum at the compressor exit. Successful control of rotating stall was achieved with an actuator whose bandwidth, 70 Hz, was less than the frequency of either the rotating stall or the rotational speed of the compressor: 100 and 180 Hz, respectively.

As regards achieving more efficient and cleaner combustion, a key consideration is in avoiding combustion instabilities. As noted in Ref. 28, such instabilities can involve large amplitude acoustic oscillations sufficient to cause mechanical or thermal damage, and passive approaches to avoiding them have generally not been satisfactory. On the other hand, tests using active control systems were shown to be promising.[28] A pressure sensor at an upstream location in the combustor, where all axial acoustic modes were expected to be significant, provided a signal processed to modulate the flow of a secondary gaseous fuel stream into the combustor, with gain and phase changing with stability characteristics in real time. The secondary fuel injector actuator had a modulation rate variable from 0 to 1500 Hz and the processor relied on an observer to "identify the amplitudes, frequencies and phases of several combustor modes in real time."[28] Among results achieved in that research were instabilities damped in 40 ms. Zinn and Neumeier concluded that a fuel injector suitable for such an automatic combustion instability controller could be integrated within existing engine fuelfeed systems.[28] Both the preceding applications of avionics components and techniques, and presumably others, to the design and operation of intelligent turbine engines seem highly likely.

Returning to Fig. 17, it is noteworthy, although not shown explicitly, that avionics system components are often provided to filter or otherwise shape the pilot commands transmitted to the aircraft's flight controls. These functions, i.e., those of Function 3, may be thought of as modifying what is seen by (they may even be part of) the PFCS in Fig. 17. There is, of course, a loop closer also not shown in this figure, from the MEP's pilot displays to the PFCS/AFCS's pilot control. This loop closing takes place as the pilot responds to situational awareness by moving the controls. Control command shaping by avionics systems components may be necessary to eliminate biomechanical feedback caused by the pilot's inadvertent response to the aircraft's oscillatory motion in the cockpit. Such response can give rise to pilot-induced (or "assisted") oscillations and be the crucial link in troublesome, even destructive instabilities.

Most important, however, in citing these examples is that multifunctional use of components results in some components acting in combinations of Functions 1–5 (although not likely in Function 2), and inner loops and outer loops. In these multifunctional situations, the most demanding frequency response, reliability (see "classification" in Table 2), or limits to authority requirements apply to each component.

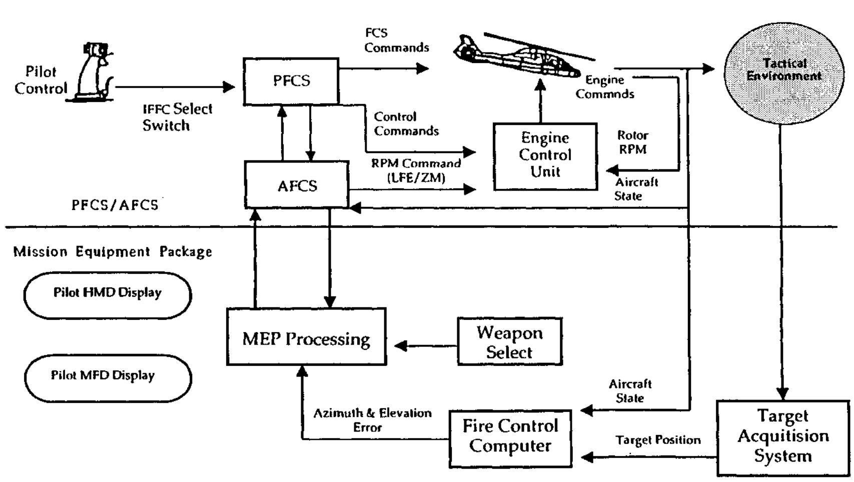


Fig. 17 Flight/engine/fire control system integration (from Ref. 11).

Advent and Impact of Smart Materials/Structures

Smart materials are thought of as those that produce electric voltages when strained, e.g., the direct piezoelectric effect, and/or become strained when subjected to electric or magnetic fields or temperature changes. Examples of the latter behavior include piezoelectric materials (the converse piezoelectric effect), magnetostrictive materials, and shape memory alloys (which change states, and thereby dimensions or shapes, depending on temperature), respectively. The strain-sensing characteristic gives piezoelectrics potential for use as sensors; the strain-inducing behavior of the last three, potential as actuators. Reference 29 provides a summary of some of the research conducted prior to 1997 in applying such smart materials as actuators in aeronautical systems. Among the unique properties of such materials for use in avionics systems are included the possibility of distributing them throughout a structure, rather than concentrated at specific points as are such sensors as accelerometers or strain gauges, or as actuators are, that drive the rotation of a control surface. In some applications, very high frequency response is available as well. Where distributed sensing has advantages, smart materials are considered for embedding as just another fiber in advanced filamentary composite materials, and embedding may be considered for distributed actuation too, but usually at a surface of the structure.

Using smart materials and structures techniques also holds promise for more spatially continuous variations of shapes and other properties, with the elimination of discontinuities in slope angles at the surface—often important from aerodynamic considerations. Hanselka et al.[30] made the case for continuously adaptive wings very well, in writing "the fixed (shape) wing has the disadvantage that it is optimized for only one design point, described by the altitude, Mach number, and aircraft weight. These parameters vary continuously during mission, while the wing geometry is seldom optimal. Thus, a fixed geometry is only a compromise solution." They went on to propose the use of smart materials that change shape according to signals from appropriate sensors, properly processed, to 1) change the camber of a Fowler flap, according to spanwise position, and 2) at the chordwise positions where supervelocities will exceed Mach 1, raising a bump that lowers wave drag at transonic speeds. They predicted results as shown in Fig. 18.

It will be noted that such applications of feedback control systems using smart structures correspond to Category I avionics systems as defined in this paper. A somewhat similar application, but involving smart material actuated changes in a steady twist angle of the primary structure of rotor blades, is being considered for tilt rotor aircraft, because of the large changes of inflow experienced by the rotor as it goes from hover to cruise speed in forward flight. Actuation is the main problem in this Category I avionics system application, as discussed in Ref. 31. Use of smart materials in Category II and III systems seems less likely, partially because aerodynamic surface motion (force effectors for flight path control) must be relatively large, and combinations of large force and large deflection are hard to achieve with smart materials, as discussed in Ref. 29.

Category IV systems taking advantage of smart materials characteristics appear more promising, particularly when combined with advanced filamentary composites as structural materials. The use of piezoelectric actuators mounted on the upper and lower surfaces of a wing, for example, whose graphite/epoxy spar was assumed to have its filaments oriented at various ply angles (measured from the aircraft's fore-aft axis) was examined in Ref. 32. Changes in still air natural frequencies were achieved for an unswept wing, as shown in Figs. 19a and 19b, where $k_p = 0$ indicates no active elements and $k_p \neq 0$ indicates moments are being applied by the piezoelectric actuation, proportional, in one case, to the wing root bending moment and, in another, to the wing tip's transverse deflection, to increase effectively the wing's bending stiffness. Note that the curves in Fig. 19a are normalized by the value of the first bending mode's frequency with a 90-deg ply angle (ϑ), i.e., when filaments are parallel to the wing's spanwise axis. In Fig. 19b, however, the normalizing frequency is taken as that for the first mode when $\vartheta = 0$ deg. In Ref. 32, the influence of smart materials on the bending-torsion aeroelastic divergence of swept-forward wings is also examined. Librescu et al. concluded that "the synergistic effect resulting from the simultaneous use of tailoring through the implementation of a proper ply-angle configuration and (feed-back) control by means of adaptive materials, produces a wing with better dynamic and static aeroelastic characteristics than would have been produced with either tailoring or (feed-back) control alone."[32]

Use of piezoelectric transducers as both sensor and actuator to increase panel flutter speeds was examined in Ref. 33. In this investigation, the sensor signal is proportional to strain rate, is amplified by the flutter suppression system, and is fed back to itself as a control signal, i.e., direct rate feedback. Piezoelectric sensioactuator location is, as would be expected, most effective where the panel's flutter mode shape has high strain, i.e., panel deflection curvature. Increases in dynamic pressure where panel flutter (a supersonic phenomenon) is encountered were predicted to be raised over 50% using this system. Limitations on effectiveness occurred when the piezoelectric sensioactuators became saturated (which is defined as the point

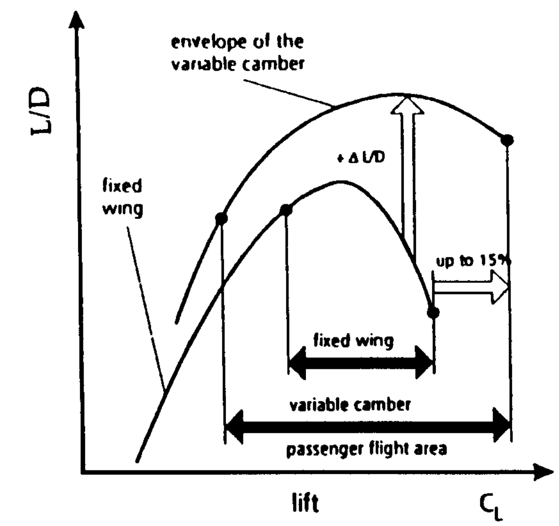


Fig. 18a Wing with variable camber.

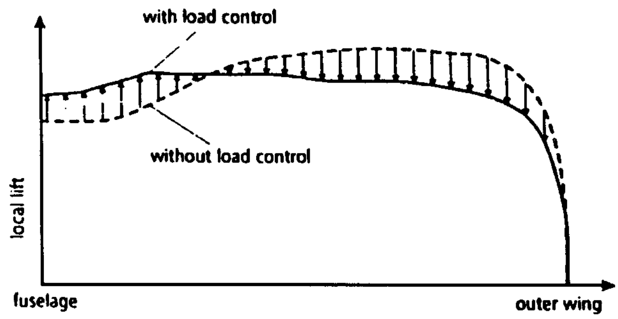


Fig. 18b Spanwise load control.

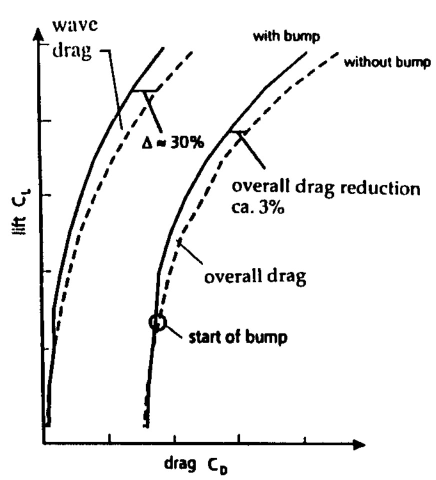


Fig. 18c Drag control with an adjustable bump.

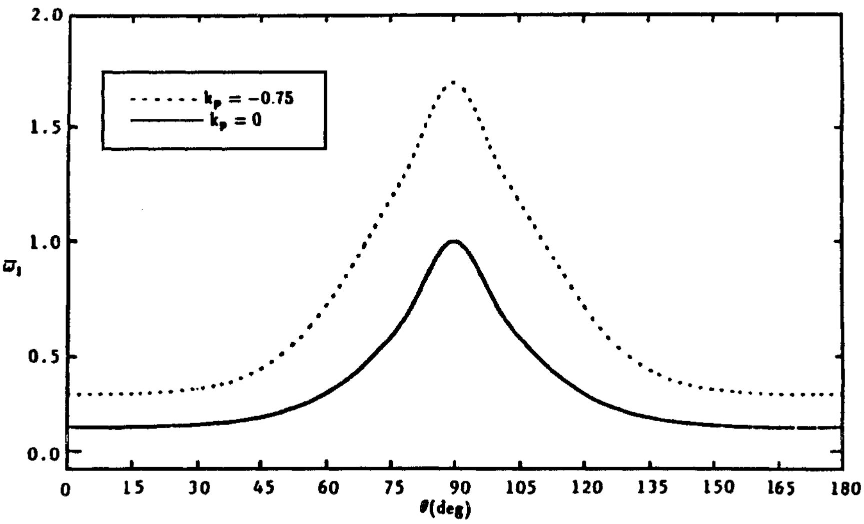


Fig. 19a First normalized coupled eigenfrequency vs the ply angle for the uncontrolled wing ($k_p = -0.75$) (from Ref. 32).

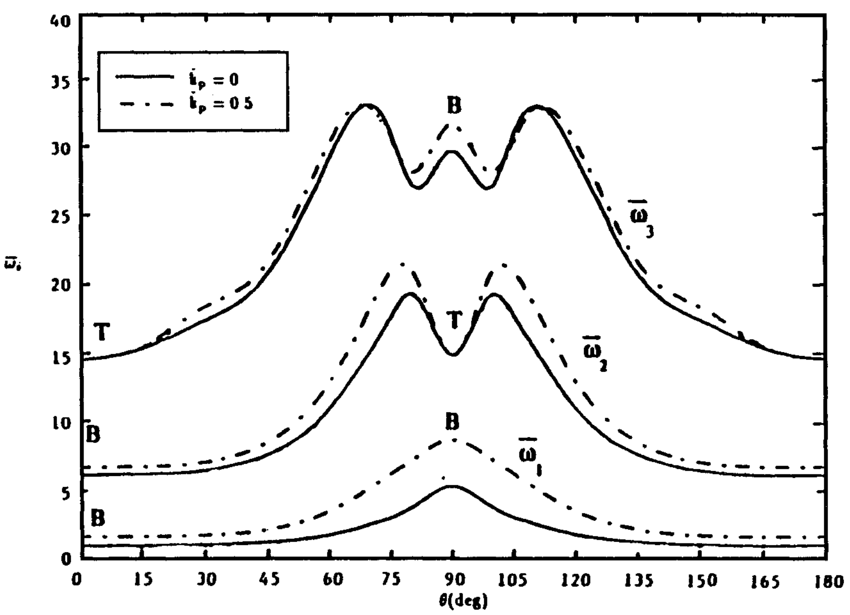


Fig. 19b Three normalized coupled eigenfrequencies vs the ply angle for the uncontrolled wing ($k_p = 0$) and the wing controlled according to transverse tip deflection ($k_p = 0.5$) (from Ref. 32).

at which increases in applied voltages no longer cause increased strains) or where a mode in which strain is low at the sensioactuator location becomes flutter-dominant.

If any aircraft with tail surfaces is placed in a sufficiently drastic attitude relative to its forward motion, and at the right value of dynamic pressure, its tail surfaces are highly likely to be buffeted. Most aircraft are designed so that these conditions will only occur outside the aircraft's normal flight envelope, but with military aircraft, particularly, the need for high AOA, and/or high yaw angle maneuvering, to attack a target or evade enemy action successfully will usually expose vertical and/or horizontal tail surfaces to buffet. The unsteady aerodynamic conditions at the tail, which are the excitation for buffet, have many sources. They can include, on helicopters, regions of flow separation, typically around the main rotor hub and its pylon fairing; on tilt rotor VTOL aircraft, which tend to have thick wings for structural reasons, from or near intersections of the wing and fuselage, or wing and tip-mounted, rotor/engine nacelles; and on modern fighter aircraft, from relatively sharp wing leading-edge extensions or the blending areas of wing/body blending. Instances of leading-edge extensions are cited in Ref. 34 as F-5, F/A-18, and AV-8B, whereas wing/body blending is used on F-16, SR-71, F- 22, YF-23, MIG-29, SU-27, B-1, and B-2 aircraft. When buffet is caused by vorticity arising from turbulent boundary-layer separation, an aerodynamic improvement can often be a major part of the solution. For fighter aircraft, however, leading-edge vortices are generated purposefully, to generate flowfields that improve lift-to-drag ratios at moderate to high AOA. It has been noted earlier that buffet excitation can have broad frequency spectra, as does atmospheric turbulence, but the purposefully generated vortex flows tend to have peaks at frequencies related to the vortex's rotational speed. In either case, tail buffet can, and usually does, involve vibrations serious enough to be considered a problem in crew and passenger compartments. It is the unacceptable reduction in the fatigue life of tail-surface structures, however, that usually calls for buffet amelioration. Buffet typically causes the lowest natural vibratory modes of the tail surfaces to respond at levels that cause the majority of this structural damage. The ramifications of such response can be aggravated, as might be expected, when one kind of surface supports another, as in "T" tail or "H" tail arrangements.

Active control of tail buffet response using smart materials like piezoelectric actuation, acceleration or strain sensors, and simple control techniques, therefore, seems increasingly attractive. Wind-tunnel experiments with such a system on a small dynamically scaled, generic twin-vertical tail fighter-model with a double delta wing were reported in Ref. 34. Testing was conducted at AOAs and dynamic pressures representative of the parts of the flight envelopes

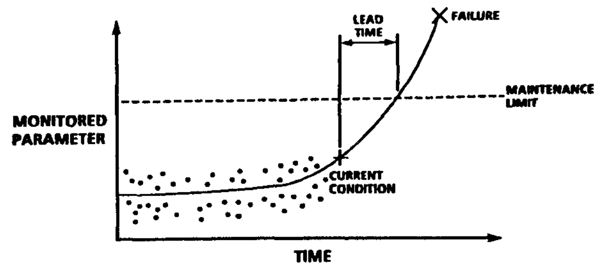


Fig. 20 Health monitoring allows early detection of faults and maintenance planning (from Ref. 36).

of actual aircraft in which tail buffet would be encountered. Piezoelectric "patch" actuators were located over most of the model's span to control the first two bending modes, and a piezoelectric torsion actuator was placed near the root. Strain gauges were collocated with the actuators and an accelerometer was mounted at the fin tip. These sensors provided signals used to minimize either root strains or tip accelerations. Reductions of up to 40% of tail buffet response for varying AOA and dynamic pressure combinations were achieved, indicating that structural fatigue life on the full-scale empennage structures could be doubled using this smart materials/avionics combination. Adaptive control algorithms were shown to be necessary because appropriate gains varied nonlinearly with the "drastic changes in flight conditions that accompany maneuvering" (Ref. 34).

Noise control in gas turbine engines is a very challenging problem. Active measures, especially those using smart materials, seem most promising. An approach for ameliorating the rotor/stator noise generated when wakes from upstream rotors impinge on stator vanes is reported in Ref. 35. It is proposed there that noise reduction in the far field be attempted using cancellation techniques by embedding as many as four piezoelectric actuators along the chord—three in the top surface and one in the bottom—of the fan exit guide vanes. Very compact actuators are required to fit the thin cross sections of the vane without adversely affecting their structural integrity, and they must operate at temperatures from 230 to 370 K (−50–+200°F) and withstand foreign object damage. For typical exit guide vanes with chords in the range of 100–230 mm (4–9 in.) and thickness ratios between 5–7%, noise cancellation requirements led to actuators of "unimorph" (i.e., flat) and "rainbow" (curved) configurations in circular planform, with 50 and 32 mm (2 and 1.25 in.) diameters, and 0.25 and 0.38 mm (0.010 and 0.015 in.) thicknesses, respectively. Designed to operate at resonance, these actuators produced maximum displacements of 0.46 and 0.33 mm (0.018 and 0.013 in.), respectively, at frequencies greater than 1 kHz. Simonich concluded that this active noise control scheme can be implemented using the kind of smart material actuators demonstrated in the reported research.[35] It is interesting to speculate as to the integration of such noise amelioration functions into future full authority digital engine control turbine engine controls, in the manner mentioned in the preceding section.

Use of smart materials as sensors of damage and/or wear has great potential in so-called health usage monitoring systems (HUMS). The benefits of such real-time diagnostic systems is depicted graphically in Fig. 20 (from Ref. 36). If the maintenance limit shown there can safely be raised closer to failure and the lead time confidently allowed to go to that maintenance limit, then replacement part inventories can be reduced for operational fleets, and man-hours and downtime for maintenance reduced. Thus, economics and safety can both be well served by HUMS. Smart materials are, of course, not the only sensors useful for such systems. The ease with which they can be embedded and distributed throughout structures, however, provides significant advantages. As in other applications of avionics, the potential for having HUMS functions incorporated with others, through the increasing capabilities of digital processors, seems very promising.

Implications for Aeronautical Engineering Education

The concept underlying most undergraduate aeronautical engineering programs is that the fundamentals of all of the foundation disciplines should be learned in sufficient depth to ensure both minimum competence in them and to engender understanding of how they are integrated into successful aircraft designs. If the capabilities of avionics are increasingly used, for example, to reduce structural weight, reduce the size of aerodynamic surfaces, improve range and maneuverability, aerospace curricula should expose students to avionics' role in aircraft design at the earliest practical point in required courses. Although this, as in all curricular matters, will require careful consideration, some actions seem likely. The introduction to aerodynamic stability derivatives, for example, might be followed immediately by the equivalent stability behavior produced by automatic feedback control of control surfaces. The first example of torsional divergence in undergraduate aeroelasticity courses could be similarly followed by showing how a generic automatic system can extend the flight envelope, and the equivalent increase in torsional stiffness evaluated for the students' edification. Single-degree-of-freedom, mass-spring-damper system response to pure sinusoidal excitation could be taught to include examples of undefined sources of opposing forces added proportional to and in phase with system output velocities.

In short, as many of the fundamental courses as seems reasonable should introduce the concepts of automatic feedback control through their applications to lead naturally to their integration into aircraft designs. Dynamics and controls courses should be offered including material to acquaint aeronautical engineering students with the kinds of capabilities and limitations to be expected with the latest sensors, processors, actuators, and other avionics systems components. Such courses should also acquaint students with what constitutes satisfactory environments for such systems. That is, while the principles of avionics controls in generic terms are introduced through their applications, some of the important practicalities should be exposed as well.

Conclusions

The first application of avionics systems to aircraft was in the form of communication and navigation systems that, although essential, had little or no influence on basic aircraft design. Over the years, however, avionics systems applications have grown to the point where they influence such crucial design parameters as acceptable mass characteristics; the size of lifting, propulsive, and stabilizing aerodynamic surfaces; and the weight of primary structure. Primary flight controls, flight path stability augmentation, load control, gust alleviation, and passenger comfort enhancement are now all functions for which avionics systems are rather routinely considered as options in the design and development of advanced fixed and rotary wing aircraft. Reliability, redundancy management, and fail-safety have been ensured for such systems to the point where the probabilities of functional failures are comparable to those of primary structure. Further, many avionics components are now integrated routinely into systems with various functions so that designers can reason, "If we have it for this, we may as well use it for that."

In spite of that, and although use of avionics systems to control aeroelastic instabilities in airframes, reducing tail buffet, and suppressing instabilities in turbomachinery—such as rotating stall and in combustion—have been demonstrated in tests (including in some cases flight tests that took place 25 years ago), these capabilities have not been taken advantage of in the conceptual and preliminary design stages of aircraft in service today to any extent. Still farther from routine application, the potential of smart materials and structures for use in health usage monitoring systems, variable camber airfoils, and noise and vibration reduction is motivating extensive research. Their nature fits very well into the burgeoning application of avionics in aeronautics because virtually every use considered for smart materials and structures makes use of avionics systems feedback and control techniques, if not actual components.

All things considered, it seems obvious that the use of avionics systems in aeronautics, which is already pervasive, will become increasingly influential at the earliest stages of design. It follows that the well-prepared aeronautical engineer should be increasingly familiar with avionics systems, their components, their capabilities, and their limitations— in short, how they can be exploited to increase performance and safety and reduce costs.

Acknowledgments

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