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Impact of Active Controls Technology on Structural Integrity

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This article summarizes the findings of an investigation conducted under the auspices of the technical cooperation program (TTCP) to assess the impact of active controls technology on the structural integrity of aeronautical vehicles, and to evaluate the present state-of-the-art for predicting loads caused by a flight-control system modification and the resulting change in the fatigue life of the flight vehicle. Important points concerning structural technology considerations implicit in applying active controls technology in new aircraft are summarized. These points are well founded and based upon information received from within the aerospace industry and government laboratories, acquired by sponsoring workshops which brought together experts from contributing and interacting technical disciplines, and obtained by conducting a case study to independently assess the state of the technology. This article concludes that communication between technical disciplines is absolutely essential in the design of future high-performance aircraft.

Introduction

THE technical cooperation program (TTCP) was formed to provide a mechanism for government organizations within Australia, Canada, New Zealand, the United Kingdom, and the U.S. to conduct cooperative research projects. The goal of TTCP is to identify areas of common interest and gaps in existing research and development (R&D) programs, provide recommendations for initiating new R&D activities, and to perform collaborative studies. TTCP is composed of subgroups that are responsible for broad areas of research where there is sufficient interest among the member countries for initiating collaborative activities. Within the subgroup structure, technical panels are formed to review and establish cooperative programs within the technical realm of the subgroup and action groups are formed to investigate specific issues. Subgroup H, which has the responsibility for aeronautics technology, established action group HAG-6 to examine and assess the potential of recent and projected advances in active controls technology (ACT) for producing significant adverse effects on the structural integrity of fixed-wing aeronautical vehicles.

To accomplish these objectives, three courses of action were pursued by HAG-6: 1) review-related activities within the government and industrial laboratories of the participating countries; 2) sponsor workshops to bring together scientists and engineers who are actively involved in the analysis, design, test, qualification, and operation of aircraft; and 3) perform an independent analysis to evaluate present state-of-the-art methodologies involved in the integration of the technical disciplines of structures, structural dynamics, aerodynamics, and active controls. For the analysis task, the F/A-18 aircraft served as the case study. HAG-6 completed the investigation and prepared a final report[1] for subgroup H in October 1989. An executive summary of the report[2] was also prepared and distributed to government laboratories and to the aerospace industry within the participating countries in March 1990. The purpose of this article is to provide an assessment of the state-of-the-art analytical capabilities, design methodologies, and qualification practices, and to highlight other related interdisciplinary issues.

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Statement of Problem

Structural Integrity/Fatigue Tests

Structural integrity is a prime concern during the development of flight vehicles. The structural design and fatigue testing of the aircraft is predicated on an assumed usage spectrum and on a related set of loads, based initially on analysis, and subsequently on wind-tunnel data. During the demonstration and validation (D&V) phase of the aircraft development process, a prototype is built and flown to obtain loads data for the flight conditions assumed to make up the fatigue load spectrum. Since operational aircraft may very well differ from the prototype, an engineering and manufacturing development (EMD) phase is required to build a group of test aircraft intended to be representative of the vehicles to be obtained during the production phase of the acquisition cycle. Flight tests accomplished during EMD are required to identify the critical points in the sky for structural design so that 100% design limit load maneuvers can be flown to measure loads and to verify structural design adequacy. The measured flight data are used to obtain the true loads for the selected flight conditions based on the design usage spectrum, and later when sufficient fleet hours have been acquired, to define a more representative set of flight conditions and a more accurate lifetime load spectrum. The load spectrum can now be compared with the design analysis and fatigue test results to adjust the design lifetime of the operational fleet.

Digital Flight Controls Technology

The introduction of digital fly-by-wire aircraft into the inventory has required the designers and the users to better understand the critical role played by digital controllers and ACT. One of the significant advantages of digital flight control system (DFCS) technology is the ability of the manufacturer to improve aircraft performance after the aerodynamic and structural designs are complete. This is accomplished through software changes, a task which can be very excruciating when the requirements for reverification and re-evaluation of software under formal configuration control must be included.

During the design of an aircraft with a DFCS, it is reasonable to expect the DFCS to evolve, through software modifications, as the aircraft progresses from the E&V phase to the EMD phase. This evolution may even continue for years after an aircraft has gone into production. It is also reasonable to anticipate that some DFCS changes may have subtle, and sometimes severe, adverse affects on the structural dynamics (aeroservoelasticity) and structural integrity (fatigue) characteristics of the aircraft. Therefore, it is expected that ACT may bring both advantages and disadvantages; for example, while ACT may be used to reduce undesirably large structural loads at one position on the wing, the improvement may be offset by increased loads at other locations. The original problem may not be solved, but merely shifted from one part of the structure to another, or from one technical discipline to another.

DFCS can also be used to limit the flight envelope of the aircraft. This is referred to as "carefree piloting." It is expected that carefree piloting will lead inevitably to an increase of severity of the aircraft flight spectrum as pilots more aggressively complete maneuvers at the envelope boundary, relying on the *g*-limiter to keep the vehicle safe. It is expected that interpretation of the fatigue test in terms of operational experience with a significantly more severe load spectrum will be very difficult.

Problem Statement

The problem statement is then, "How can we assure that the design and modification of an active control system has been properly evaluated such that system impacts on structural integrity, particularly, negative impacts can be assessed?"

Case Study Investigation

Answering this question requires a thorough understanding of the structural integrity, structural dynamics, aerodynamic, and active controls technical disciplines, and the methodologies for integrating these disciplines. An analytical study was undertaken to independently evaluate the capability of modern, linear analytical methods to predict the change in wing loads resulting from a change in a DFCS. For this study the interaction of structures, aerodynamics, and controls (ISAC) code[3] and the flexible simulation (FLEX-SIM) code[4] were used. Since the F/A-18 (Fig. 1) is a relatively new high-performance aircraft with a DFCS, it was selected as the case study.

F/A-18 Background Information

For background information, the F/A-18 fatigue test was initiated in 1979 using the approach described earlier in this article. After a few hundred hours of testing, the F.S. 453 carry-through bulkhead failed and a new bulkhead had to be fitted onto the test article. Later, other problems were encountered which lead to the conclusion that significant portions of the fuselage structure were not adequately designed. As a result, a new center fuselage section was fitted into this test article. By the time the fatigue test was ready to resume, sufficient flight testing of the aircraft with the DFCS modified to include a load alleviation system had been completed and loads data measured. The fatigue test was resumed using a new loads spectrum based on the lower wing loads caused by the load alleviation system. The completed fatigue test ultimately demonstrated four lifetimes on the forward fuselage and wings, nearly four lifetimes on the aft fuselage, and over two and one-half lifetimes on the replaced center fuselage. Military design specifications require that only two lifetimes be demonstrated during the test.

In terms of the F/A-18 flight control system, the DFCS has four redundant computers working in parallel. Programmable read-only memory (PROM) holds the operational flight program which consists of the run-time executive, control laws, redundancy management, and built-in test functions. Redundant electrohydraulic servoactuators and analog sensors provide two-fail-operate control capability. There are 10 independent primary control surfaces consisting of (in pairs) stabilators, rudders, ailerons, leading-edge flaps (LEF), and trailing-edge flaps (TEF). The LEF and TEF deflection and command limits are scheduled as functions of angle-of-attack, dynamic pressure, and Mach number. These schedules are designed to minimize drag during cruise, to improve high angle-of-attack characteristics, to improve spin departure resistance, and to provide flap load alleviation at elevated load factors.

As is typical for any modern DFCS software, the F/A-18 operational flight software went through experimental evo-

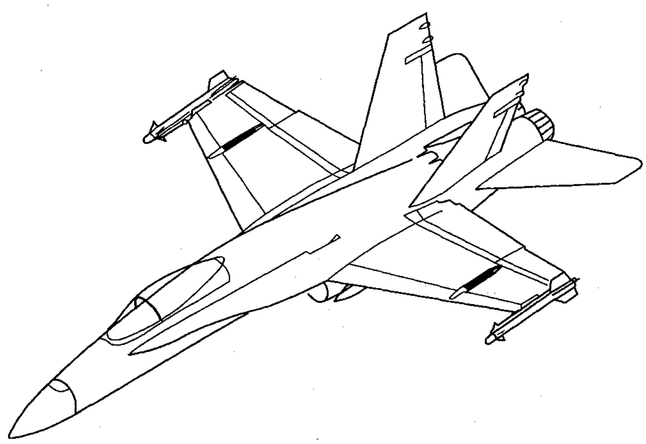

Fig. 1 Schematic of the F/A-18.

lutionary changes during the full-scale flight testing phase. One of the objectives of the DFCS experiments was to develop a production load alleviation system to reduce wing bending moments. Two successive PROMs involved in the load alleviation system development, PROM V4.3.1.3 and PROM V4.3.2, are studied herein. The basic LEF and TEF position schedules of the F/A-18 are a function of angle-of-attack, airspeed, and Mach number, and they are identical for both DFCS PROMs. However, the PROM V4.3.2 configuration included additional LEF and TEF position increments which were a function of Mach, altitude, and incremental load factor. These increments were an initial attempt to define a load alleviation system. PROMs V4.3.1.3 and V4.3.2 also incorporated a special development feature called the "fixed flap mode." In this mode the pilot could select a particular LEF and TEF position, overriding the scheduled positions. Another difference between PROMs V4.3.1.3 and V4.3.2 is the way dynamic pressure and Mach limits were imposed on the flap schedules. In the PROM V4.3.1.3 system these limits stopped flap scheduling and set the flap position to zero and were placed after the command generated by the fixed flap mode. Thus, the effect of scheduled flap position on wing bending moment above these dynamic pressure and Mach limits could not be investigated. The PROM V4.3.2 configuration placed these limits before the command from the fixed flap mode. Thus, the fixed flap mode command overrode the limit command.

Flight Test Data

The F/A-18 flights involving the load alleviation system PROMs described above are identified as flight 164 (PROM V4.3.1.3 implemented) and flight 167 (PROM V4.3.2 implemented). Flight data, which included pitch stick force, normal load factor at the aircraft c.g. (Nz), average stabilator position, average LEF position, average TEF position, and wing-root bending moment (WRBM) were obtained for identical maneuvers (7.5 g symmetric pull-up at Mach 0.85, 2000-ft altitude). Figures 2 and 3 show plots of these measured pa-

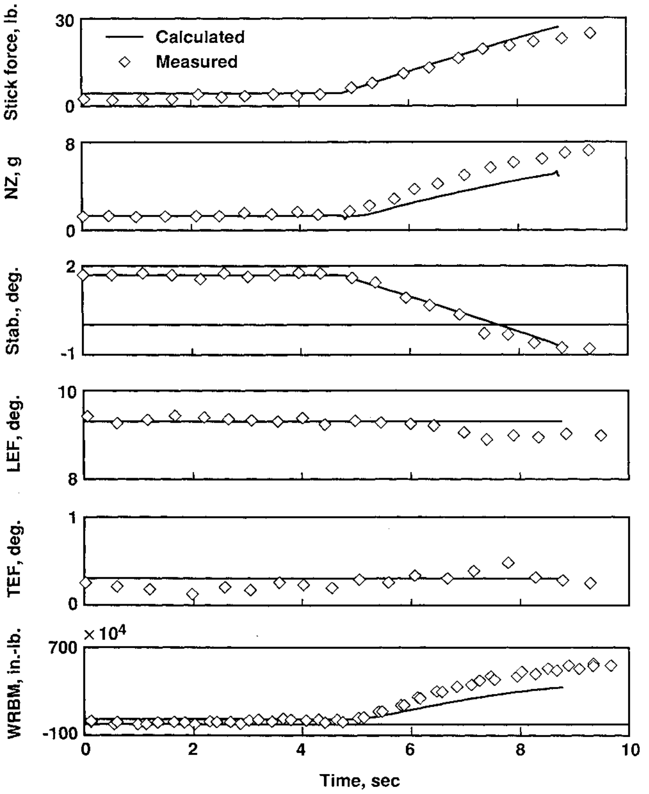

Fig. 2 Comparison of measured and ISAC-calculated data for flight 164, PROM V4.3.1.3.

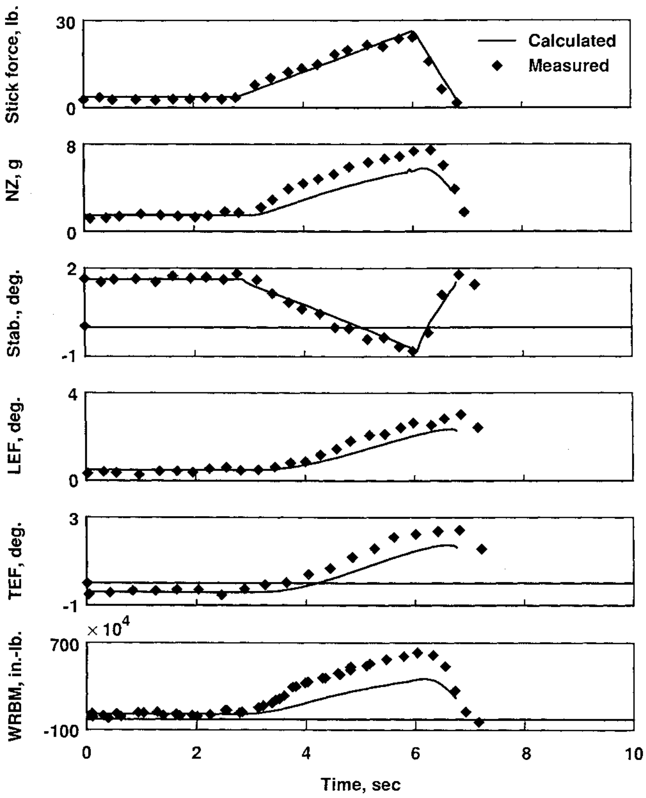

Fig. 3 Comparison of measured and ISAC-calculated data for flight 167, PROM V4.3.2.

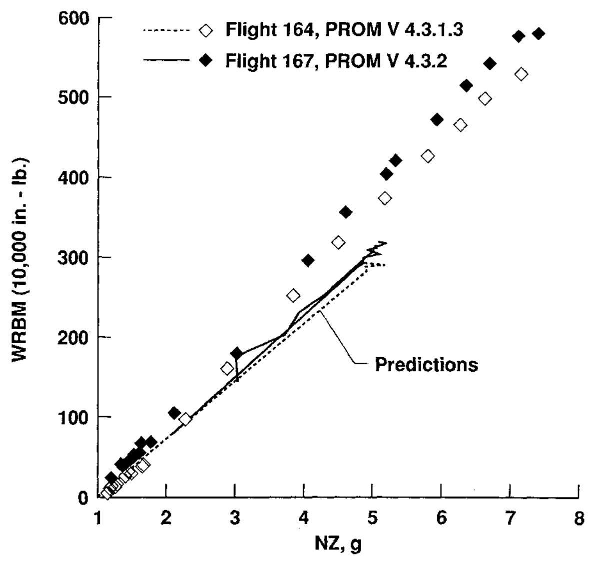

Fig. 4 Comparison of measured and ISAC-calculated bending moment per *g*.

rameters vs time for the two flights. Figure 4 shows the variation of WRBM as a function of Nz.

Flight 164 incorporated the PROM V4.3.1.3 DFCS with the fixed flap mode. The data in Fig. 2 shows the LEF at approximately 9-deg down throughout the maneuver. If the DFCS were in its normal mode, the LEF would have been at about 1-deg down or less during 1-*g* flight and would have scheduled during the maneuver. In a similar manner, the TEF is at about 0.25 deg and also does not schedule during the maneuver in the data of Fig. 2. The data for flight 167 (Fig. 3) show the LEF and the TEF scheduling during the maneuver. The data from Figs. 2 and 3 clearly show that the WRBM is lower with the flap setting used during flight 164 than that obtained with the baseline load alleviation system used during flight 167.

During the early stages of the flight test program, comparisons of this type served as the impetus for continuing further studies to obtain a production load alleviation system. The load alleviation development process of adjusting the LEF and the TEF via the fixed flap mode, flying the maneuver, and measuring the wing bending moments was repeated many times. A set of data that gave wing bending moment as a function of flap position, Mach number, Nz, angle-of-attack, etc., was obtained. Based on this data a flap schedule that minimized wing bending moment was developed. This flap schedule was implemented in a later 6.0 DFCS configuration for flight test evaluation and ultimately in the production 8.3 DFCS configuration.

ISAC Analyses

Symmetric analyses were performed to obtain information to compare with the data measured during symmetric flight test maneuvers. For this study, the plunge and pitch rigid-body modes and the first 10 symmetric flexible aircraft modes were used to develop the half-aircraft equations of motion. Modal load coefficients were determined by applying the mode shapes to the finite element structural beam model as unit displacement fields. The internal loads consisted of the six stress resultants: two bending moments, one torsion moment, two shears, and one axial force. The coefficients were combined with time histories of the modal coordinates to produce time histories of the internal loads. The doublet lattice method[5] was used to calculate the subsonic steady and unsteady aerodynamics. For the aerodynamic analysis the aircraft was represented as a series of flat plates (Fig. 5) with the wing, stabilator, and fuselage being coplanar while the vertical tail was positioned at the correct dihedral. The DFCS was modeled using the appropriate sensors, actuators, and control laws.

The ISAC predictions of aircraft response and load time histories for the DFCS tested on flight 164 (PROM V4.3.1.3) are presented as solid lines in Fig. 2, and for the DFCS tested on flight 167 (PROM V4.3.2), as solid lines in Fig. 3. The calculated and measured control surface deflections show reasonable agreement; the comparison of normal load factor shows similar trends, but the magnitudes differ by as much as 36% for the PROM V4.3.1.3 setting and 40% for the PROM V4.3.2 setting. Figure 4 provides comparisons between measured and calculated values of WRBM as a function of normal load factor for both flights. The calculated curves have lower slopes than do the corresponding measured values and differences of about 30% for both DFCS PROM configurations. Both the calculated and measured results show an increase in the WRBM for a given normal load factor following the modification to the DFCS.

FLEX-SIM Analyses

An analysis of the F/A-18 aircraft was also conducted using a group of computer codes linked by a system known as FLEX-SIM. Identical modal data were used in this analysis as were used by ISAC to develop the equations of motion. A steady-state panel method was employed to represent the full aircraft modeled as a flat plate of equivalent planform. For the dynamic forces associated with the elastic modes an unsteady aerodynamics program by Davies[6] was used independently for the wing and tail. The steady and unsteady aerodynamics were then combined and utilized to formulate the equations of motion. The prediction of loads on the lifting surfaces was accomplished using both the modal displacement method described earlier and the modal acceleration method described by Bisplinghoff and Ashley.[7] For the latter method the load is evaluated as the direct summation of externally applied forces plus the aerodynamic forces resulting from the motion minus the inertia loads due to motion in both the rigid aircraft and elastic mode freedoms.

The predicted responses and loads on the F/A-18 with the PROM V4.3.1.3 DFCS (flight 164) are compared in Fig. 6. It is seen that the predicted normal load factor closely follows

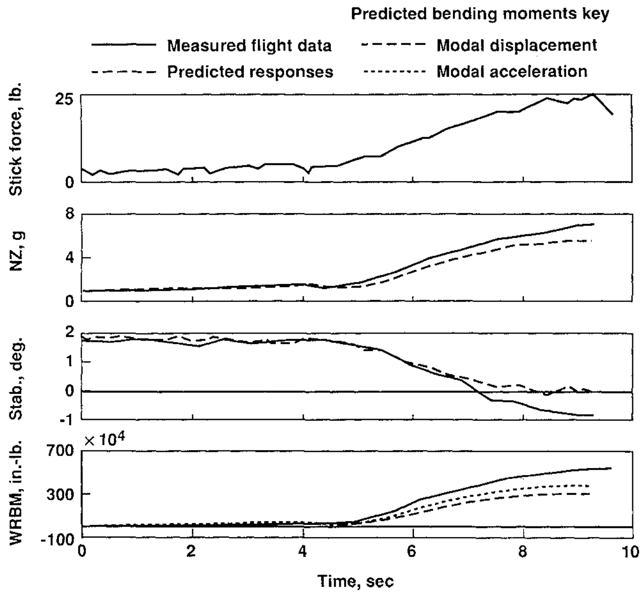

Fig. 6 Comparison of measured and FLEX-SIM-calculated data for flight 164, PROM V4.3.1.3.

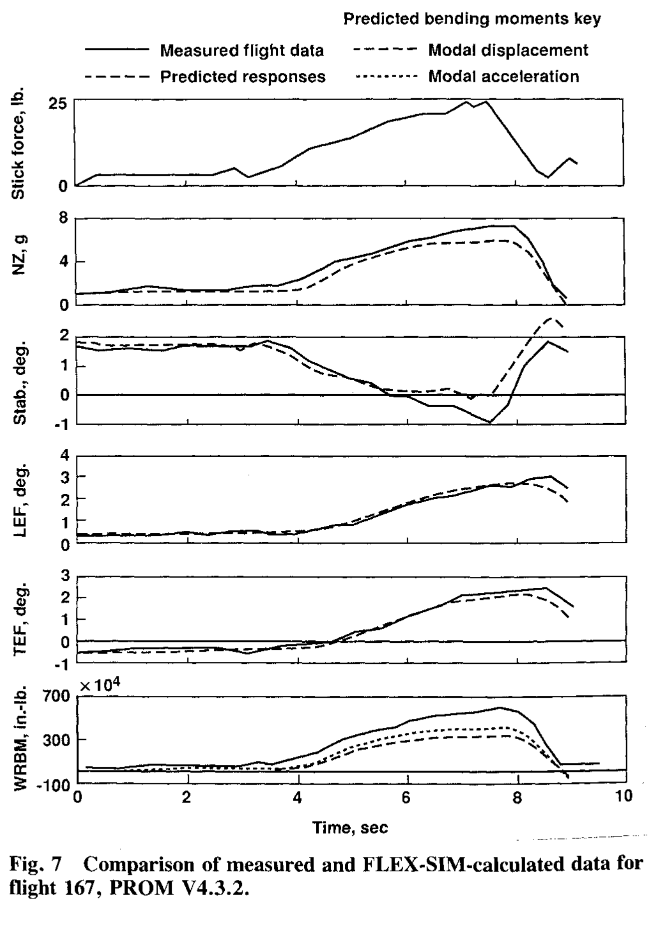

Fig. 7 Comparison of measured and FLEX-SIM-calculated data for flight 167, PROM V4.3.2.

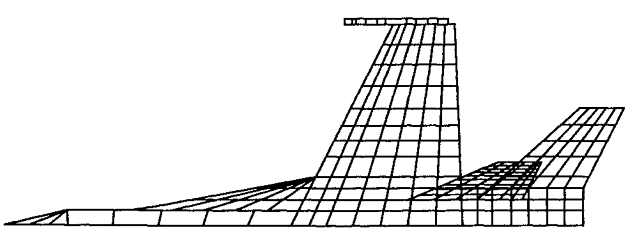

Fig. 5 Aerodynamic box pattern.

the flight-test values except for a slight reduction in the later stages of the maneuver, building up to a 20% deficit. In addition, there is a 27% difference in the magnitude of the stabilator deflection. The two versions of bending moment show the modal displacement prediction to be lower than the modal acceleration curve, which itself is about 30% too small as compared to flight data. The predicted responses and loads on the F/A-18 with the PROM V4.3.2 DFCS (flight 167) are compared in Fig. 7. For normal load factor the simulation gives a peak which is 18% less than the observed increment. The corresponding deficits for the peak control surface deflection differences were 30% for the stabilator, 12% for the LEF, and 11% for the TEF. The bending moments predicted by both methods show a greater reduction from the measured data; the modal acceleration method again has a peak value 30% less than the flight data. Normalizing the bending moment by reference to the normal load factor gives a traditional and useful parameter for wing root loads in symmetric motion. Calculating the ratio of incremental bending moment to incremental normal load factor for the measured data on flight 164 gives a mean value of 87.9×10^4 in.-lb/g, whereas the modal acceleration method gives 80.6×10^4 in.-lb/g. The effect of the load alleviation control law changes on flight 167 are to modify these values to 95.1×10^4 in.-lb/g measured and 83.8×10^4 in.-lb/g predicted. The flight data show an 8.3% increase in loads due to the modification while the calculations gave a 3.9% increase.

Assessment of Needs

Based on the results of the case study and other HAG-6 investigations and workshops, an assessment of needs was established; these needs are summarized below.

Interaction of Disciplines

The application of structural optimization for the minimization of weight quite often results in lower elastic mode frequencies. ACT is being utilized with an ever-increasing bandwidth of operation. As a consequence, there is a strong tendency for structural dynamics and the active control systems to interact. The potentially destabilizing effect of the sensors feeding back structural mode dynamics becomes more significant as the designer's confidence grows, allowing even further increases in control gains. ACT greatly extends the freedom to configure a vehicle. If full advantage is to be gained from this flexibility, the aerodynamic, structures, and controls disciplines must work together as an integrated team during conceptual and preliminary design phases.

The segregation of technical disciplines as related to this study, unfortunately, is continuing. This appears to be due, at least in part, to the differences in the nature of the disciplines and the grouping of specialists into work units that combine aeroelasticity and controls, but do not include structural integrity or fatigue. The deterministic nature of aeroservoelasticity makes it accessible and relevant during the design/testing phase of aircraft production. On the other hand, fatigue is probabilistic in nature and is perceived as being more pertinent to the mature phase of aircraft operation. In order to be prepared for the future, the integration of certain disciplines is a necessity for the analysis and design of high-performance vehicles. For this reason, the communication gaps between various technical disciplines needs to be eliminated, particularly between the areas of ACT and structural integrity (fatigue).

The integration of disciplines for effective ACT studies is partly a matter of developing mathematical techniques and applying these procedures in a broader field. It also involves a management problem. The traditional compartmentalized approaches to design must be fundamentally changed to allow the relevant specialists to work closely together without encountering the barriers established between the offices of the separate disciplines.

There is, furthermore, a need to rapidly and completely monitor structural loads at all stages of the aircraft development process and to have these loads readily assessed as the control systems are being designed or enhanced. As a result of ACT expanding the flight envelope, many more critical loading cases arise than ever occurred for passively controlled aircraft.

Analytical Requirements

With respect to the effects of control functions on structural integrity and fatigue life, the critical technical disciplines are currently segregated. Because dissimilar mathematical models are used, controls/dynamics analysts have no incentive or common basis to communicate with fatigue and fracture experts. At the present time, one of the more significant payoffs associated with an aircraft having a DFCS results from the ability to perform rapid and "relatively inexpensive" modifications to the system as an alternative solution to structural changes in the aircraft. It is recognized that more substantial benefits could be gained by the optimization of the DFCS during the design phase of the aircraft rather than in response to deficiencies demonstrated during flight or fatigue testing. Early consideration of ACT requires the integration of technologies, thus emphasizing the need for multidisciplinary analysis and design codes.

Fatigue in aircraft structures most commonly results from localized high stresses at joints as a result of the stress concentration of the rivets, bolts, or pins. Accurate calculation of the value of the localized stress in all fatigue critical areas is beyond the capability of present finite element methods. This is of particular concern since a 10% difference in stress may lead to a factor of about 2 in fatigue life. There is, therefore, much to be gained by improving analytical techniques to provide more accurate predictions of flight loads and resultant localized stresses.

At present, the only practical method of determining the fatigue life of an aircraft is by means of a full-scale fatigue test with loading representative of operational conditions. The difficulty of ensuring that the loading is representative, coupled with the ease with which the role and loading of the modern aircraft can be changed by reprogramming the DFCS, means that a realistic assessment of the fatigue life of the aircraft cannot be completed until after the aircraft has spent some years undergoing tests and evaluation. After the aircraft is produced and changes to the DFCS occur for one reason or another, the resulting loads should be lower, thus guaranteeing an increase in the fatigue life.

Design optimization including fatigue life for aircraft incorporating a DFCS will remain a difficult, if not impractical, proposition for some time. The statistical nature of fatigue and the strong dependence upon detailed stress magnitudes ensure this assessment. At the present time there appears to be no prospect of changing the situation.

The accuracy in the prediction of steady and unsteady aerodynamic loads at subsonic, transonic, and supersonic speeds is insufficient to define the loads for structural integrity and fatigue life evaluations. In addition, present methods are unable to predict load changes with respect to a change in an active control system to the degree of accuracy necessary to quantify the effect on fatigue life. Thus, more precise tools are needed in the loads prediction area. Especially important for fighter aircraft is the need for an improved method to determine the dynamic response of structures under the influence of separated flow and subjected to random aerodynamic loading. An example is vertical fin buffeting due to a leading-edge extension vortex. Furthermore, unsteady aerodynamic loads resulting from control surface deflections are not accurately predicted, especially for novel types of control surfaces, for spoilers, or when large deflections are involved. Hinge moment is a notably difficult quantity to predict and is critical for defining the required control system capabilities.

Design Requirements

Aircraft performance is a major parameter considered during selection of a new aircraft. The selection process is generally dominated by the views of the aircraft pilots. In addition, it may be relevant that the time scale for any deficiencies in the aircraft to appear be a consideration of the selection team. Operational inadequacies are apparent soon after the aircraft becomes operational, but fatigue problems may not be revealed until the aircraft has been in service for a number of years. In other words, the design process needs to be reassessed with an eye towards including more fatigue considerations in the early stages.

Since design requirements are largely founded on satisfactory experience with previous generations of aircraft, the incorporation of ACT may represent such a large deviation from the past that a number of underlying assumptions become questionable. Examples on transport aircraft include the maneuver and gust load design requirements. The maneuver case demands the structure withstand a specific symmetric pull-up normal acceleration, and the gust case specifies a certain gust velocity. These values together are based on combined gust and maneuver data collected on aircraft very different from current and future transports, and are a representation of an idealized loading environment that would have been equivalent to the observed real life data on early aircraft. There is no guarantee that this equivalence holds after changes in such factors as size, speed, geometry, and the use of ACT. Moreover, modern structural design capability and the application of ACT load alleviation allows the strength of the structure to be tuned very closely to just meet the requirements, whereas earlier generations of transports carried a certain excess weight (and hence, strength) because it was not possible at that time to control the design process so closely.

Modern gust load alleviation (GLA) systems are designed principally to moderate the effects of large gusts, thereby eliminating the danger of stress overloads. These systems generally have a threshold beyond which the GLA becomes activated. This threshold is necessary to prevent possible actuator and control-rod fatigue resulting from the small but frequent gust load occurrences. While the small gusts are not important from the point of view of overload, they may make a significant contribution to wing-root fatigue. This contribution may be amplified by the removal of the high gust loads (by the GLA system) that may actually be beneficial to fatigue life through crack growth retardation effects of occasional high loads.

Another problem associated with the interpretation of load alleviation is the relative safety implied by the excess margin from design load to ultimate load. This margin covers many unknowns and variabilities in all parts of the requirements and loading predictions. An apparent degradation of safety arises when a load alleviation system is effective up to design limit load, but saturates before reaching the ultimate load. With the system saturated, the loading gradient reverts to that of a passive aircraft, and the ultimate load is reached for a smaller increment of input gust or maneuver, and therefore, a smaller proportion of the design load than for an aircraft without ACT. More consideration should be given to the philosophy behind the application of these safety factors to aircraft with ACT.

Data Requirements

Regarding wind-tunnel testing, model programs are continually needed to calibrate analytical and design codes and to further investigate unusual flow phenomena and the subsequent loads on flight vehicle structures. Pressure fluctuations from flow separations are especially difficult to predict, but can be measured during wind-tunnel tests using rigid models. These measurements provide the driving force in aeroelastic response investigations. The motion-induced unsteady loads, which are important to dynamic response and flutter predictions, are strongly coupled to the separated flow. Currently, there is no practical theoretical method to predict unsteady loads associated with separated flow.

Another consideration is the lack of available gust data. There have been a number of turbulence measurement investigations that involved fully instrumented research aircraft and poorly instrumented commercial aircraft. Collection of gust data on operational aircraft is the only way to obtain realistic samples of rare severe events that are comparable to the design gust severity. Advances in digital data collection and recording now permit the possibility of measuring turbulence or maneuver response data on operational aircraft, thereby providing a valuable and much needed data base. For combat, aircraft current turbulence models are sufficiently accurate for ride control studies. However, there are still some unanswered questions concerning the amplitude of turbulence to be encountered, especially as terrain following systems allow the aircraft to fly lower than ever before.

Design Philosophy

ACT has been used to improve aircraft performance in a rigid-body sense for many years. In the last 20 yr significant advancements and applications in ACT towards the control of elastic modes have become quite evident. More recently, the analog FCS has been replaced by digital systems. The DFCS offers many advantages over an analog system. These advantages include the capability to implement sophisticated control laws and redundancy-management methodologies, and cheaper and repeatable performance. However, as a result of some of these advantages, there has been a rapid growth in the application of DFCS/ACT highlighting the need for an assessment of the impact on aircraft design philosophy. Initially, these benefits were largely seen in the ability to improve or rectify deficiencies in the aircraft structural or flight performance by changes in the DFCS, rather than by more expensive structural changes. The logical extension back into the initial design phase of the aircraft suggests the need for reassessment of some of the traditional views regarding aircraft design. Some of the conservatism adopted in earlier military aircraft design philosophies may be in danger of erosion due to competing economic pressures.

The recent advent of DFCS in aircraft has opened the way for a major change in aircraft design philosophy incorporating ACT. The DFCS offers versatility at reasonable cost compared to the earlier analog systems. Increased application of ACT as a result of the benefits offered by the DFCS may be seen in each of the three main phases of the aircraft life. During the initial design ACT confers an advantage by way of reduction in required structural strength in such applications as gust and maneuver load alleviation. Following aircraft production, DFCS/ACT offers new opportunities to overcome aircraft performance deficiencies that appear during flight testing or structural weaknesses that may become apparent during fatigue or other structural integrity testing. After the aircraft enters service, the search for increased performance, the desire for a change in role for the aircraft, or the need to overcome fatigue problems may all be aided by the application of ACT.

It is not unusual for the load spectra of military aircraft fleets (and some civil fleets) to change significantly over the life of the aircraft. For a fighter aircraft this can be as a result of increased pilot familiarization with the aircraft capability, development of new flying techniques or maneuvers, or a change in the role of the aircraft. The last reason may result from the tendency, particularly in recent times, for an aircraft to be required to undertake dual roles such as air combat and ground attack, or from development of new stores/weapons/roles in addition to those available when the aircraft entered service. The DFCS/ACT in modern aircraft will exacerbate this trend towards more severe flight spectra. In particular, the ability to provide carefree piloting by appropriate programming of the DFCS enables development of flying techniques that may have a high potential for aircraft overstress.

It is expected that removing the need for the pilot to maintain a safety margin will lead inevitably to an increase of severity of the aircraft flight spectrum. Squadron pilots will most likely complete maneuvers at the envelope boundary more aggressively relying on the g-limiter to keep the vehicle safe. Furthermore, the inability to overstress the aircraft has emphasized the need to reassess the reasons behind the choice of aircraft limit load. Traditionally, there has been a factor (usually 1.5) relating service limit load and proof load. This factor has been assumed to take account of the probability of accidental overstress, variability of the mechanical properties of the aircraft materials and uncertainties in the calculation of flight loads, and the structural strength of the aircraft. The relative magnitudes of the contributions (to the factor of 1.5) are difficult to estimate. It would, therefore, be inadvisable to reduce the present safety factor because of the introduction of the g-limiter, even if the overstress prevention system could not be overridden.

Design Rectification

The DFCS/ACT can be modified more readily during the flight-test phase than the structure could be changed after construction. This flexibility may be used to enhance handling or performance, usually to overcome deficiencies discovered during the tests, but carries structural implications. If gross changes to control surface utilization are made after the fatigue test has been completed, it becomes almost impossible to interpret the test results in terms of the new configuration. The static strength test could also be reduced in applicability. Another problem of ACT changes during the flight-test program is that structural load clearance must be repeated for the modified system. Given the characteristics of ACT for expanding the range of conditions for which critical loads may be encountered, this implies a considerable validation exercise.

Despite the recent advances in the capability to predict aeroservoelastic characteristics, there remains the possibility of instabilities caused by structural feedback to the control system. Checking for these requires lengthy ground tests of the complete aircraft. If a problem is encountered, then a costly rectification program may be required. Changes to the filter configuration in the control system or repositioning of ACT sensors will need to be evaluated and retested before the program can continue. Consequent changes to structural loads will also need to be checked.

Operational Considerations

The presence of an active control system can have a substantial influence on how a pilot flies his aircraft, which, in turn, can cause the true loading spectrum to diverge from that originally estimated by the designers. For example, after an automatic g-limiter was installed on an aircraft, the number of acceleration exceedances at any given g-level per flight hour increased dramatically. As another example, an airline pilot who is flying with a nonfunctioning GLA system might be compelled to yield a wider berth to thunderstorms to avoid turbulence. For any given active control function, the designer needs to assess not only how its addition will enhance performance, but also how this addition will change the pilot's operational behavior. This involves a need for additional communication between the designers and operational personnel.

Another area of concern is that the performance of an ACT system must be maintained throughout the life of the aircraft. If the required performance and reliability that were predicted at the design stage are to be achieved, then the system must remain fully serviceable. Minimum dispatch conditions must be observed on every flight to ensure that the full probabilistic performance is followed and failure modes are analyzed for any undesirable departure from predictions. The actuators and controls are likely to require greater care and attention than on earlier aircraft, and the control freeplay may become particularly important. A large value of freeplay may degrade performance of the active system, decrease flutter stability, or introduce oscillatory loadings.

Conclusions

The conclusions resulting from this investigation are summarized as follows:

1) The capability to improve aircraft performance and/or to redistribute aerodynamic loads by reprogramming a DFCS is expected to be exploited when flight or fatigue testing reveals deficiencies from design specifications. As a result, the interpretation of the full-scale fatigue tests will become quite difficult.

2) The opportunity to optimize aircraft control systems for maximum performance throughout the flight envelope increases the number of flight conditions for which critical load cases may arise, thus increasing the task of structural clearance.

3) The potential for a DFCS to adversely affect aircraft fatigue is not being adequately considered or investigated by the aircraft manufacturers and users. In addition, there is very little ongoing research in the combined fields of structural dynamics, structural integrity, active controls, and aerodynamics. This lack of activity has caused solved control or aeroelastic problems to reappear in the form of fatigue problems.

4) State-of-the-art analytical tools used in the case study were inadequate for predicting the absolute levels of loads on aircraft with active controls. Therefore, it was not possible to calculate stresses at critical locations with sufficient precision to make accurate predictions of aircraft fatigue life. The possibility of incorporating fatigue life as a parameter in any approach to aircraft design optimization is, therefore, precluded unless significant advancements in load prediction capability are first obtained.

5) The computer codes used in the case study were capable of calculating the change in load resulting from the change in the DFCS. Predictions corroborated the increase in the WRBM as experienced in flight. Therefore, it is possible to predict increments in loads thus permitting a quantitative assessment of the impact of DFCS changes on fatigue life.

6) The knowledge and understanding of the loads on transport aircraft, especially aircraft with GLA systems, is not well-established. The same concern exists for military aircraft with other active control concepts. In particular, the lack of modern data on gusts is of concern. This is true for both the smaller magnitude gusts responsible for most fatigue damage and for severe gusts.

Recommendations

This article highlights the integration issues related to structural dynamics, aerodynamics, active controls, and structural integrity and provides evidence that suggests very little interaction between researchers in these fields. Since multidisciplinary cooperation will be a necessary step towards improving the designs and reducing the life-cycle costs of new aircraft, research activities dealing with multidisciplinary integration should be more aggressively pursued. Since increased interaction is needed between experts in these disciplines to narrow the gaps in knowledge and communication throughout the aerospace industry, continued workshops which stress the interaction and integration of key technical disciplines are recommended. Studies to develop and apply multidisciplinary technology and the exchange of key technical experts from different disciplines are also recommended to develop a common basis of terminology, equations, and tools.

The following are examples of specific technical disciplines requiring serious consideration for integration: 1) linear and nonlinear, steady and unsteady aerodynamic codes; 2) aerodynamic correction factor methodologies; 3) structural finite element modeling; 4) fatigue life prediction; 5) structural optimization; and 6) active control system modeling. As always, further activity is required in the areas of wind-tunnel testing for code validation, ground and flight testing for verification of multidisciplinary concepts, flight measurement of gust and maneuver data, and detailed analysis of operational usage data for improving structural integrity design methodologies.

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