

ESTABLISHING CONFIDENCE IN CCV/ACT TECHNOLOGY

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SUMMARY

Despite significant advancements in Controls Configured Vehicles/Active Controls Technology (CCV/ACT) in the past decade, few applications of this promising technology have appeared in recent aircraft designs. This paper briefly summarizes the status of CCV/ACT, describes some of the constraints which are retarding its wider application, and offers some suggestions toward establishing an increased level of confidence in the technology.

INTRODUCTION

Major advancements have been accomplished in flight control technology during the past decade, particularly in the areas of fly-by-wire, active controls and, more recently, digital controls. The next generation of U. S. commercial transports must take advantage of benefits achievable from these advanced techniques to remain competitive in the world market. European aircraft industries have major advanced flight control programs underway and are making significant progress in this field. The United States space program, research aircraft programs and military advanced development programs have brought ACT digital FBW (fly-by-wire) technology to a level where substantial benefits can be realized in the near future. However, the commercial aircraft industry, airline industry, and government civil aviation agencies must be convinced that an aircraft designed around this advanced technology will achieve predicted performance and be safe, reliable, operationally practical and cost effective. Commercial acceptance of any new technology will occur only when sufficient test data are generated to clearly demonstrate that these criteria can be met with reasonable risk on a new airplane design.

Most of the progress to date in this field has been accomplished primarily on four aircraft: the XB-70, B-52, F-4 and F-8. Programs on these aircraft are making significant necessary contributions, but the programs are experimental in nature, conducted to demonstrate concept feasibility under carefully restricted flight conditions in evacuable military aircraft with ejection seats. This paper briefly summarizes the state-of-the-art of CCV/ACT technology and suggests some approaches to the problem of developing a wider level of confidence in that technology.

BACKGROUND

In the past decade, potential benefits of advanced flight control technology have been shown by a large number of theoretical analyses and by several USAF and/or NASA flight demonstration programs. Table I summarizes briefly the results of most of these efforts. References 1 and 2 provide a more complete summary.

Major Air Force experimental flight research programs involving load alleviation and fatigue damage rate reduction by structural mode control techniques were the B-52 LAMS (Load Alleviation and Mode Stabilization) and the XB-70 GASDSAS (Gust Alleviation and Structural Dynamic Stability Augmentation System) programs. Concurrently, an advanced stability augmentation system (SAS) was developed and incorporated on the B-52G and H fleet to reduce fatigue damage rate during low level, high speed flight. The Air Force Control Configured Vehicle (CCV) research program has completed flight demonstration of four ACT concepts at selected flight conditions on a B-52E aircraft: ride control, flutter mode control, maneuver load control, and augmented stability. In addition, the compatibility of a LAMS system with these four concepts was also demonstrated. Goals for each concept were successfully achieved individually and collectively during the program.

Other flight programs have incorporated limited ACT concepts in recently designed military and commercial aircraft. Reduction of lateral gust loads on the L-1011 transport with an advanced yaw damper resulted in a 20 percent reduction of limit design loads. A Gust Response Suppression System has been developed for the 747 to improve passenger ride qualities in the aft section. The system is currently being evaluated by Qantas Airways. A ride control system is being designed for the B-1 strategic bomber, using structural mode control techniques, to improve crew ride qualities during terrain following missions. An Active Lift Distribution Control System (ALDCS) is being designed for the C-5A airplane to reduce wing design limit maneuver and gust loads and wing fatigue damage rate. The General Dynamics prototype lightweight fighter, the YF-16, has a quadruply-redundant analog, FBW control system without mechanical backup. Relaxed inherent stability is integrated into the aircraft design to reduce drag and gross weight.

The first serious commitment to including an ACT concept in a commercial transport occurred during the recent National SST program. The SST was configured with relaxed longitudinal static stability to achieve necessary gains in range-payload from reduced gross weight and drag. Experience gained from development of fail-passive and fail-operational/fail-passive autoland systems at Boeing during the 1960's provided confidence that a suitable flight control system could be developed to meet SST safety and operational requirement

The resulting SST longitudinal command and stability augmentation system providing basic airplane safety was fail-operational squared (fail-operate after second failure), utilizing quadruply redundant sensors, analog electronic channels and actuators. A mechanical reversion back-up mode was retained (a discussion of this system is contained in Reference 3).

Cancellation of the SST program precluded thorough development and flight test evaluation of the SST flight control system. Advanced technology items which include electronic display and control system components were, however, government funded for further development under the DOT/SST Technology follow-on program (Contract DOT-FA72-WA-2893).

Full realization of advanced control function potential on production aircraft depends on fly-by-wire control systems with a reliability consistent with the function criticality. Two programs, the Air Force F-4 680J Survivable Flight Control System and the NASA F-8C digital fly-by-wire program, are directed toward developing and flight demonstrating FBW systems on fighter aircraft. As a result, Reference 4 states that "with successful completion of the 680J flight test program, analog fly-by-wire control techniques, equipment mechanization and fundamental criteria are now fully validated".

Most advanced FBW flight control systems have used analog implementation techniques. Research is now underway to exploit the advantages of digital control, demonstrated, in part, by the Apollo space program. The recent extremely rapid progress in microcircuitry has made digital control hardware competitive with analog hardware in terms of cost, reliability, size and weight. Further, digital techniques offer significant advantages for advanced control laws, redundancy logic and built-in testing functions. One of the first programs to study digital flight control implementation problems on aircraft is the NASA F-8 program which successfully demonstrated a single channel digital FBW primary flight control system with a triply redundant analog backup system. Other digital control research programs, such as the Digital Avionics Integrated Systems (DAIS), the SST Follow-On Technology, and the planned Tactical Aircraft Digital System (TADS), are contributing to this technology base. Other Air Force programs are investigating the application of multiplexing techniques to flight control systems. Further, research efforts within the U. S. and European flight control system component manufacturers are studying fiber optics for providing signal transmissions immune to electromagnetic interference.

An overall assessment of advanced flight control technology over the past decade indicates that considerable progress has been achieved:

- o Performance of CCV functions has been flight demonstrated on a large flexible aircraft
- o Digital and analog FBW systems have been flight demonstrated on fighter aircraft
- o A prototype lightweight fighter has been designed around CCV analog FBW techniques.

CONSTRAINTS ON THE USE OF CCV/ACT TECHNOLOGY

Despite the large amount of analytical and flight test data available, no CCV/ACT concepts are currently in general use in commercial transport aircraft. Only the simplest form of augmented stability--the yaw damper--is in widespread use in commercial aircraft today. Primary applications are to improve handling qualities and to increase the comfort level of the crew and passengers. In a few instances, a yaw damper was necessary for certification. Although these are examples of beneficial applications, the systems were generally added after the airplane was designed, sometimes after the first model flew. In most instances, a much greater benefit would have been possible if a full-time directional stability augmentation system had been assumed from the beginning of the design.

There are a number of constraints that have effectively delayed the widespread implementation of these systems. A most fundamental constraint is risk, principally on the part of the airframe manufacturer. As has been pointed out, the maximum potential benefit of these advanced concepts is achieved if they are incorporated into the design at the outset. However, the final assessment of the benefit results from an exhaustive design process that is expensive and time consuming, and for which the correlation with hardware results is not at all certain. The real risk is that a major problem may arise after program commitment of an airplane design predicated on successful system performance.

Figure 1, reproduced from Reference 46, illustrates this concern. At program go-ahead, with only 3% of the eventual total program cost actually spent, management action can influence total program cost by 20% at most. Consequently, a program that relies on advanced systems will either require a significant increase in analysis confidence, or a program structure like the U. S. SST where an engineering prototype precedes production commitment. In other words, one way of eliminating the risk is to have a "proof before use" program plan, which adds to program time and cost.

Another constraint is the cost of these systems, including development, certification, and maintenance cost. Bright spots in the cost picture are the rapidly developing field of digital systems for aircraft applications and the reductions in analog/digital system cost disparity.

A third constraint is the lack of confidence in the analysis tools and the correlation between analytical models and the real world. For example, if a new airplane were to depend on flutter mode control for flutter safety, there would be little margin for error between the analytical model and the hardware. Yet the state of the art of flutter analysis can accomplish this today only by "fine tuning" the analysis with hardware data.

A final constraint is the reluctance on the part of the user, the airlines, to increase maintenance costs. Consequently, there is great reluctance to buy a system, almost independent of its performance benefits, unless there is a proven method of keeping the maintenance burden in hand.

It is generally true that maintenance constitutes about one-quarter of the total direct operating costs for current airplanes. Therefore, complexity such as discussed here should be accompanied by systems designed to hold the line on, or lower, maintenance costs. Digital systems, with improved self-check capability, may provide a solution to this problem.

REMOVING THE CONSTRAINTS: DEVELOPING CONFIDENCE

Commercial realization of the benefits associated with advanced control concepts will occur only when these constraints are removed through comprehensive development and demonstration of necessary methods and components.

Flight Demonstration

Most of the progress to date in this field has been accomplished primarily on four aircraft: the B-52, F-4, F-8 and XB-70. Programs involving the military aircraft are making significant necessary contributions, but the programs are experimental in nature, conducted to demonstrate concept feasibility under carefully restricted flight conditions in evacuable aircraft with ejection seats.

The next logical program should expand this technology base by developing and flight demonstrating an operationally practical advanced digital fly-by-wire control system on a commercial aircraft. The system should be designed to function throughout the flight envelope, from takeoff to landing, under normal and extreme operating conditions. It should include appropriate redundancy management, automated system test, system control, and system status and advisory displays. Extensive flight testing must be conducted to define system performance (compared to analytical predictions), reliability, failure effects, and maintainability requirements under conditions representative of commercial airline operation. Realistic design criteria and design guidelines should be developed, based on results of the program, for critical and noncritical control functions. This program should also be responsive to technology recommendations expressed in the NASA Research and Technology Advisory Council report (Reference 47).

A flight demonstration program formulated to satisfy these objectives and requirements could best achieve credible test results by utilizing a current state-of-the-art, operational, commercial aircraft as the test vehicle. The NASA RSFS airplane is well qualified as a test vehicle for demonstrating certain elements of an advanced control system. This aircraft is currently

being converted into a commercial-type research vehicle under Department of Transportation SST Technology Follow-On Program and NASA Research Support Flight System contracts (References 55 and 56). Arrangement of the new experimental flight control, navigation, and display equipment being installed for the RSFS is shown in the cutaway view of Figure 2. The aircraft features an aft flight deck (AFD) from which a two-man crew may fly the airplane from takeoff to landing with controls electrically coupled to the standard 737 flight control system. Advanced electronic systems include triply redundant digital automatic flight control computers and an advanced digital navigation, guidance, and display system. A data acquisition system provides experimental data for postflight analyses. The complete system (sensor to control surface output), which has an electronic fail-operative capability, is limited to a single thread actuation capability.

The current and planned use of the aircraft is for extensive NASA research programs regarding flight in the terminal area. The experience obtained during these programs in the operation and performance of the fail-operational sensor and computer system will be directly applicable to advanced control system development.

The aircraft, as currently configured, has the capability to provide meaningful performance, reliability, and maintainability test data in a limited-cost flight program. The aircraft could also be modified to provide sufficient system redundancy and capability to more completely model, and thereby provide better data on, the performance benefits, reliability, and maintainability of these systems. This possibility is being explored by Boeing-Wichita under contract to NASA-Langley.

Redundancy Management

The redundancy required for a flight-critical control system depends to a great extent on the mechanization scheme adopted, as well as the failure characteristics of the system under consideration. Similar considerations apply whether the element is a mechanical actuator or an electronic element. DOT-sponsored research (References 53 and 54) examined the elements of the U. S. SST prototype control system and identified problem areas associated with the redundancy of those systems, e.g., channel interactions, failure detection, and failure effects on system performance. A NASA-sponsored study (Reference 27) reviewed ten current actuator redundancy mechanization schemes and identified two concepts that would meet advanced airplane flight control system requirements.

These results are cited as evidence that work is proceeding in this area. But it must be pointed out that since computation and actuation are key elements of any control system, the promise of advanced controls will not be realized until the technology for providing adequate reliability with reasonable system cost is in hand. Appropriate research must be carried out in this area of redundancy management to ensure that the design capability is available when needed.

Improved Analysis Techniques

Existing methods cannot provide the technological base for the design of airplane configurations that rely on a control system for structural design load reduction, flutter envelope expansion, or stability when balanced for optimum performance. Some of the more fundamental problem areas are: transonic, nonlinear, and unsteady aerodynamics; interaction of structural deformation and control surface deflections with aerodynamic loading; and the dynamics of large flexible structures. Reference 47 points out that these problems "have been painfully evident to aeroelasticians for at least three decades."

Current analytical capability must be expanded to provide adequate treatment of these problem areas. Analytical methods for the rapid incorporation of experimental data into the analyses should be pursued with the objective of successfully treating separated flow regions and nonlinearities due to discontinuities. The methods resulting from this work should be verified through correlation with wind tunnel and flight test data. A few tentative steps are being taken in this direction, but much additional work remains.

In the past, wind-tunnel testing of dynamically scaled airplane models has proven economically desirable to predict airplane dynamic characteristics prior to flight testing. As aircraft become more dependent on stability augmentation systems, wind-tunnel testing of aeroelastic models to prove control concepts will become increasingly more attractive to increase confidence in analyses, as discussed in Reference 48.

In 1967, AFFDL and NASA-Langley jointly initiated a program to demonstrate an active modal suppression system on a one-thirtieth scale B-52E aeroelastic model in the Langley transonic dynamics tunnel. This model includes aileron and elevator actuation systems and provisions for a cable mount system (Reference 49). Model gust responses have been obtained using the airstream oscillator system installed in the tunnel (Reference 50). Boeing-Wichita is assisting NASA in developing a ride smoothing system for the model using 50 Hz bandwidth aileron and elevator actuation systems. Subsequently, canards and flaperons were added for RC and FMC testing, which is now nearing completion. In 1974 a MLC system will be tested.

In addition, wind tunnel tests have been conducted at NASA-Langley on a SST wing model which utilizes a FMC system (References 51 and 52). Wider use of such models will be of great benefit in CCV system synthesis and test.

Results of the recently completed B-52 CCV program indicate that precise mathematical models may not be quite as vital as stated above. Inaccuracies in the math model may be made tolerable by intelligent location of force producers, and use of motion sensors located at several different points in the structure to be controlled (Reference 57).

CONCLUDING REMARKS

Within the past decade a great amount of work has been performed to demonstrate benefits of active controls technology, yet today applications of this technology are few. The best way to develop confidence in these concepts is to flight demonstrate the concepts on a commercial transport under normal and extreme operating conditions. Such a program will clearly demonstrate and establish confidence in CCV/ACT technology.

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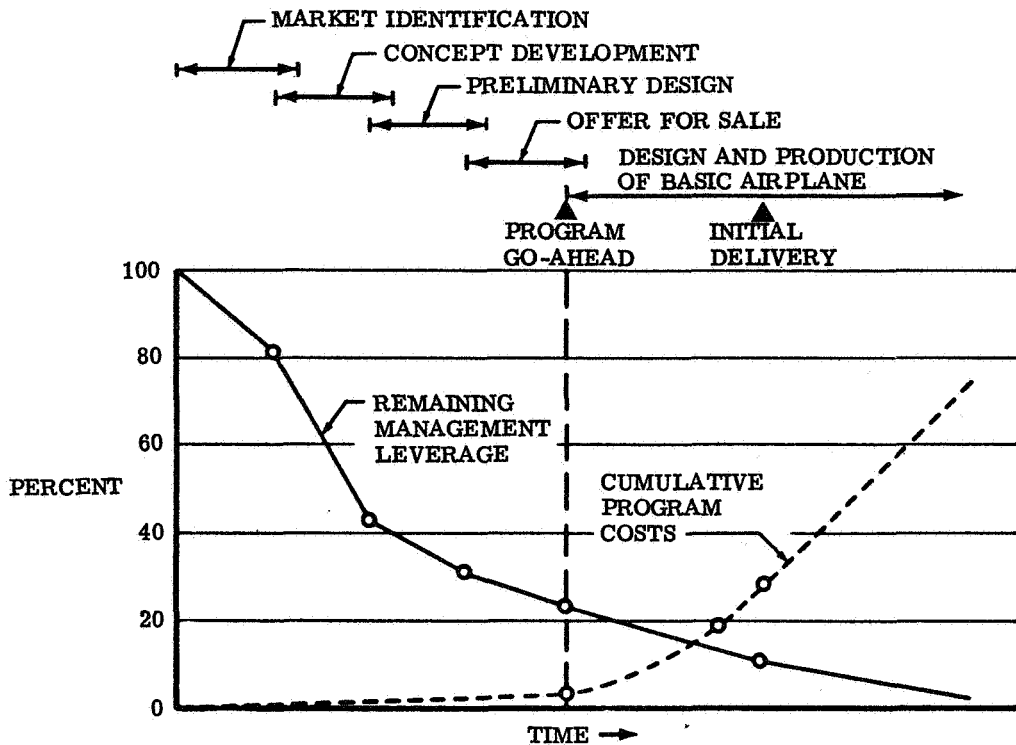


FIGURE 1. COST MANAGEMENT OF A TYPICAL COMMERCIAL PROGRAM

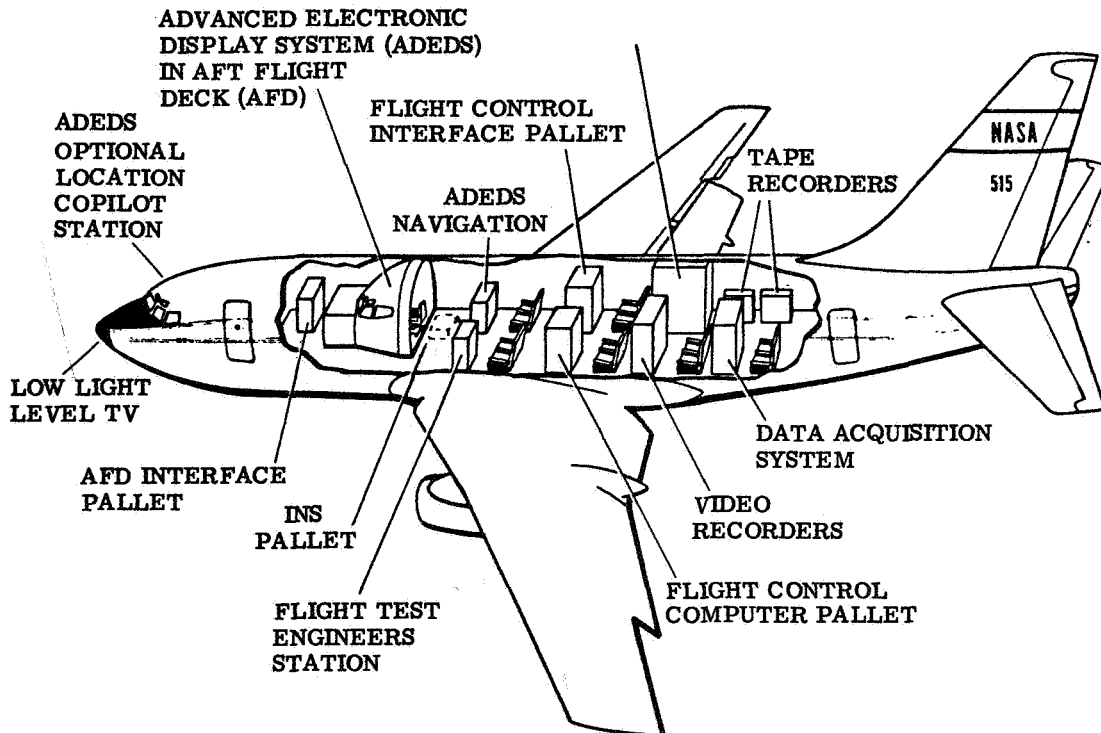


FIGURE 2 - RESEARCH SUPPORT FLIGHT SYSTEM - INTERNAL ARRANGEMENT

**TABLE I
CCV/ACT PERFORMANCE PAY-OFF STUDIES**

CCV/ACT A/P STUDIED OR TESTED	AUGMENTED STABILITY (AS)	GUST LOAD ALLEVIATION (GLA)	FATIGUE REDUCTION (FR)	MANEUVER LOAD CONTROL (MLC)	RIDE CONTROL (RC)	FLUTTER MODE CONTROL (FMC)	
BOMBERS AND TRANSPORTS	B-52	13.7% G. WT. REDUCTION POSSIBLE. SEE REFS. 5-6. CCV PROGRAM (REF. 57) FLIGHT DEMO. WITH NEUTRAL STATIC LONGITUDINAL STABILITY.	SEE REFS. 8-18	SEE REFS. 8-18	5% G. WT. REDUCTION POSSIBLE SEE REFS. 5-6. CCV PROGRAM FLIGHT DEMO. 10% REDUCTION IN WING ROOT BENDING DUE TO MANEUVERS. (REF. 57)	CCV PROGRAM (REF. 57) FLIGHT DEMO. 30% ACCELERATION REDUCTION AT PILOT'S STATION, BOTH VERTICAL & LATERAL.	CCV PROGRAM (REF. 57) FLIGHT DEMO. 30% EXTENSION IN FLUTTER PLACARD.
	XB-70			SEE REFS. 19-25	SEE REFS. 19-25		
	C-5A			SEE REFS. 26-27	LOAD DISTRIBUTION CONTROL SYSTEM (LDCS) FLOWN IN 1969. (REF. 27)		
	LOCKHEED DOUBLE-DELTA SST					50% VERTICAL ACCELERATION REDUCTION. (REF. 28)	
	LIGHT WING-LOADING STOL TRANSPORT		MECHANICAL FLAP LWL DESIGN APPROX. 12% LIGHTER G. WT. THAN EXT'L BLOWN FLAP DESIGNS. (REF. 29)			VERTICAL ACCEL. ≤ .11 g'S RMS. LATERAL ACCEL. ≤ .055 g'S RMS. (REF. 30)	
	LARGE JET TRANSPORT (700,000 LB. CLASS)				MLC PROVIDED 10,000 LB PAY-LOAD INCREASE. (REF. 31)	35-50% RED'N. IN GUST -INDUCED LATERAL ACCELERATION IN 747 AFT BODY (REFS 2 & 58)	
	U.S. SST	6,000 LB. WT. SAVINGS. 2.5% CRUISE DRAG REDUCTION (REFS. 32 & 45).				SEE REF. 33	SEE REF. 33
	ADVANCED TECHNOLOGY TRANSPORT	SEE REFS. 34-35	SEE REFS. 34-35		SEE REFS. 34-35		
	B-1					70% REDUCTION IN CREW STATION ACCELERATION. SEE REFS. 36 - 38	
	L-1011		20% REDUCTION IN LATERAL GUST DESIGN LOADS (REF. 27)				
FIGHTERS	TSR2	10% WEIGHT DECREASE, 7% PROFILE DRAG RED'N. (REF. 39)					
	F-4	SEE REFS. 40-42			SEE REFS. 40-42	150 KT. FLIGHT ENVELOPE EXPANSION (REF. 43)	
	70,000 LB. FIGHTER (BOEING MODEL 818)	14% G. WT. RED'N POSSIBLE (REF. 6)			7.5% G. WT. RED'N POSSIBLE. (REF. 6)		
	YF-16	APPROX. 10% NEGATIVE STABILITY MARGIN (REF. 44)					