IMPLICATIONS OF CONTROL TECHNOLOGY ON AIRCRAFT DESIGN

Steven M. Sliwa and P. Douglas Arbuckle
NASA Langley Research Center
Hampton, Virginia

First Annual NASA Aircraft Controls Workshop
NASA Langley Research Center
Hampton, Virginia
October 25-27, 1983

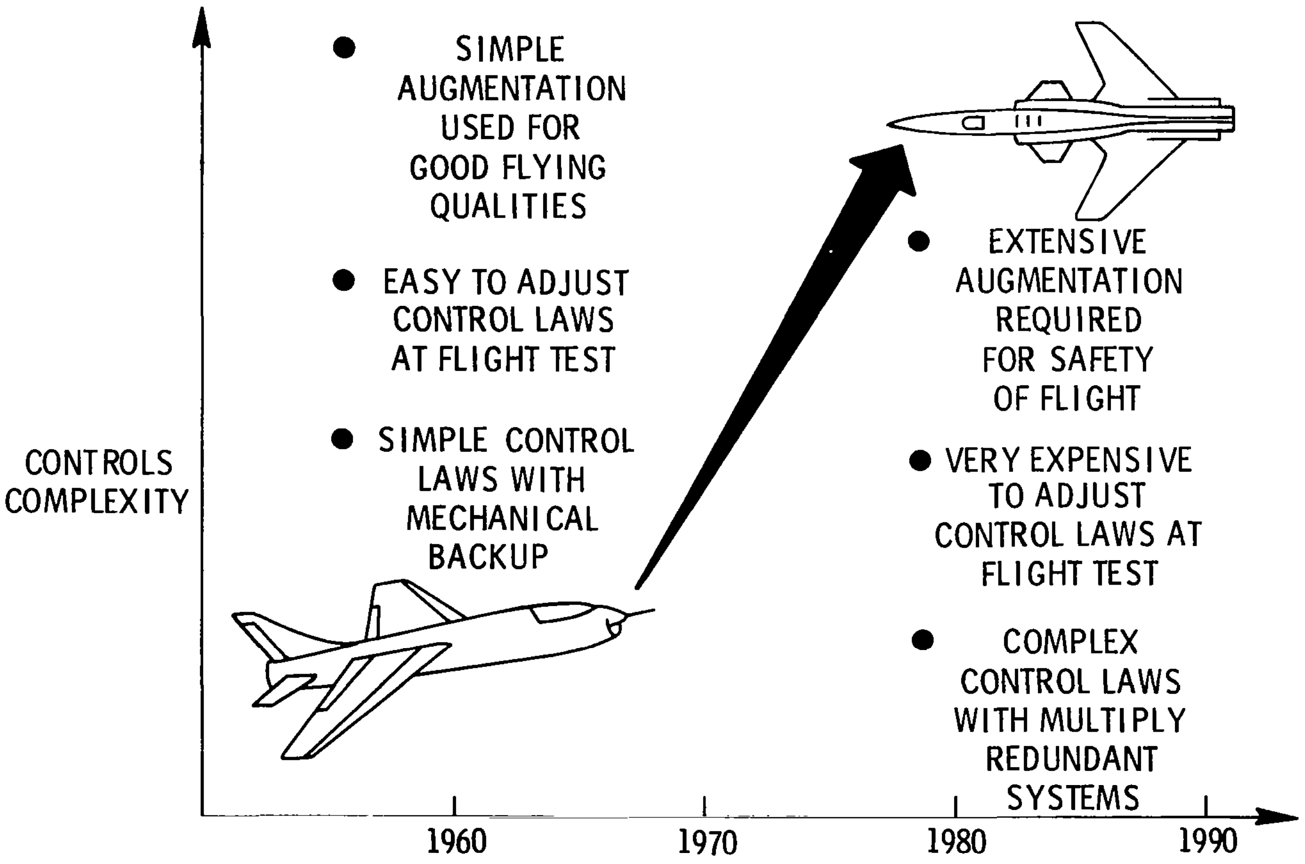
ABSTRACT

New controls technologies are now available for implementation with aircraft systems. Many aircraft with state-of-the-art technology in the fields of aerodynamics, structures, and propulsion require extensive augmentation merely for safety of flight considerations in addition to potential performance improvements. The actual performance benefits of integrating the new controls concepts with other new technologies can be optimized by including such considerations early in the design process. Recently, several advanced aircraft designs have run into considerable problems related to control systems and flying qualities during flight test, requiring costly redesign and fine-tuning efforts. It is no longer possible for the aircraft design to be completed prior to getting the controls specialists involved. The challenge to the control system designer has become so great that his concerns must be considered at the conceptual design level. A computer program developed at NASA for evaluating the economic payoffs of integrating controls into the design of transport aircraft at the beginning will be described.

- NEW CONTROLS TECHNOLOGIES ARE AVAILABLE
- MANY NEW AIRCRAFT REQUIRE ADVANCED CONTROLS
- EXPENSE OF FINE TUNING CONTROL SYSTEMS FOR CURRENT STATE-OF-THE-ART AIRCRAFT HAS RISEN DRAMATICALLY
- INTEGRATING CONTROLS INTO DESIGN PROCESS IS BENEFICIAL
- A TOOL HAS BEEN DEVELOPED TO EVALUATE THE PAYOFFS OF CONTROLS INTEGRATION

INCREASE IN CONTROLS COMPLEXITY

During the past 20 years, the control systems being used on state-of-the-art aircraft have improved significantly. In the 1950's and 1960's, simple control laws were being applied to improve the flying qualities. In contrast, current configurations may require extensive augmentation for safety of flight as well as for good flying qualities. Because of this, and because of the increased complexity of all aircraft systems, it has become extremely difficult to fine-tune or adjust control laws during flight test. Redesign efforts currently require significant amounts of engineering, which result in costly delays. Previously, very simple control schemes were used merely for improving flying qualities, and mechanical back-up systems were always utilized in the event of electronic component failure. Now, highly complex laws which rely on the improved reliability of digital and analog circuits use redundant systems for back-up modes. These examples illustrate some of the fundamental issues facing a control system design engineer today.



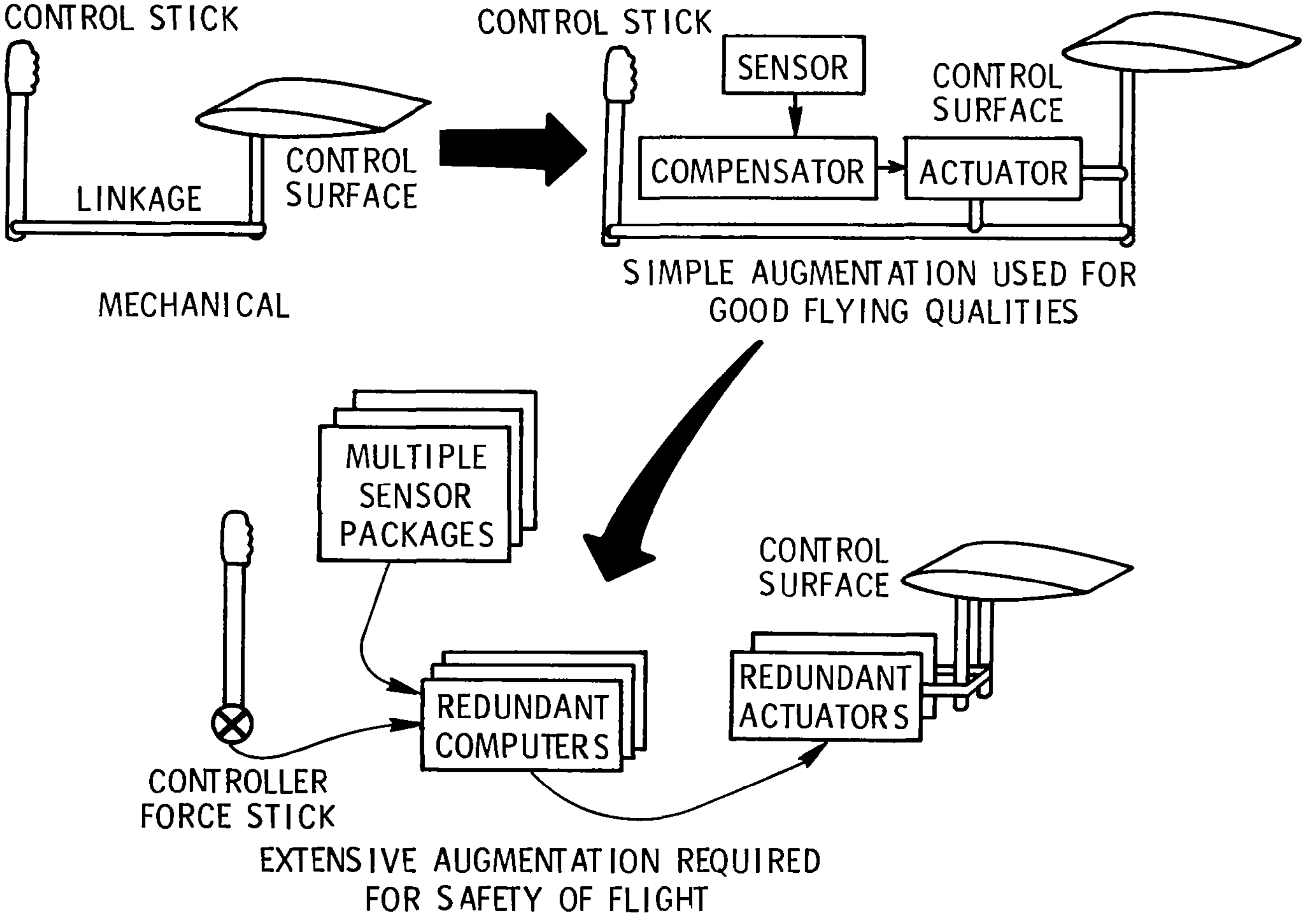
COMPARISON OF CONTROLS TECHNOLOGY

A comparison of some of the characteristics of early automatic control systems for aircraft and those being applied to current configurations is shown below. Initially, control systems were designed using simple single-loop analyses for aircraft with limited envelopes where rigid airframe assumptions were adequate. Now flexible aircraft with expanded envelopes have significant aeroservoelastic interactions that cannot be ignored during control system design. The current tendency is to develop digital fly-by-wire control systems utilizing complex multi-input, multi-output design techniques with sophisticated redundancy management. Clearly, to achieve the full potential of applying these technologies, the controls integration must occur early in the design process.

<u>THEN</u>	<u>NOW</u>
• MECHANICAL LINKAGES	• DIGITAL 6 DOF FLY BY WIRE
• SIMPLE YAW DAMPER WAS ONLY AUGMENTATION	• COMPLEX CONTROL LAWS WITH HIGH-ORDER COMPENSATORS
• SIMPLE SISO DESIGN TECHNIQUES USED DURING CONTROL SYSTEM DESIGN	• COMPLEX MIMO DESIGN TECHNIQUES USED DURING CONTROL SYSTEM DESIGN
• RIGID AIRFRAME ASSUMPTION GOOD	• AEROSERVOELASTIC INTERACTIONS IMPORTANT
• LIMITED ENVELOPE	• EXPANDED ENVELOPE
• SIMPLE CONTROL MODES	• NEW, COMPLEX CONTROL MODES
• REDUNDANCY THROUGH MECHANICAL STRENGTH	• REDUNDANCY THROUGH MULTIPLE SYSTEMS
	• NEED FOR CONTROLS INTEGRATION EARLY IN DESIGN EFFORT

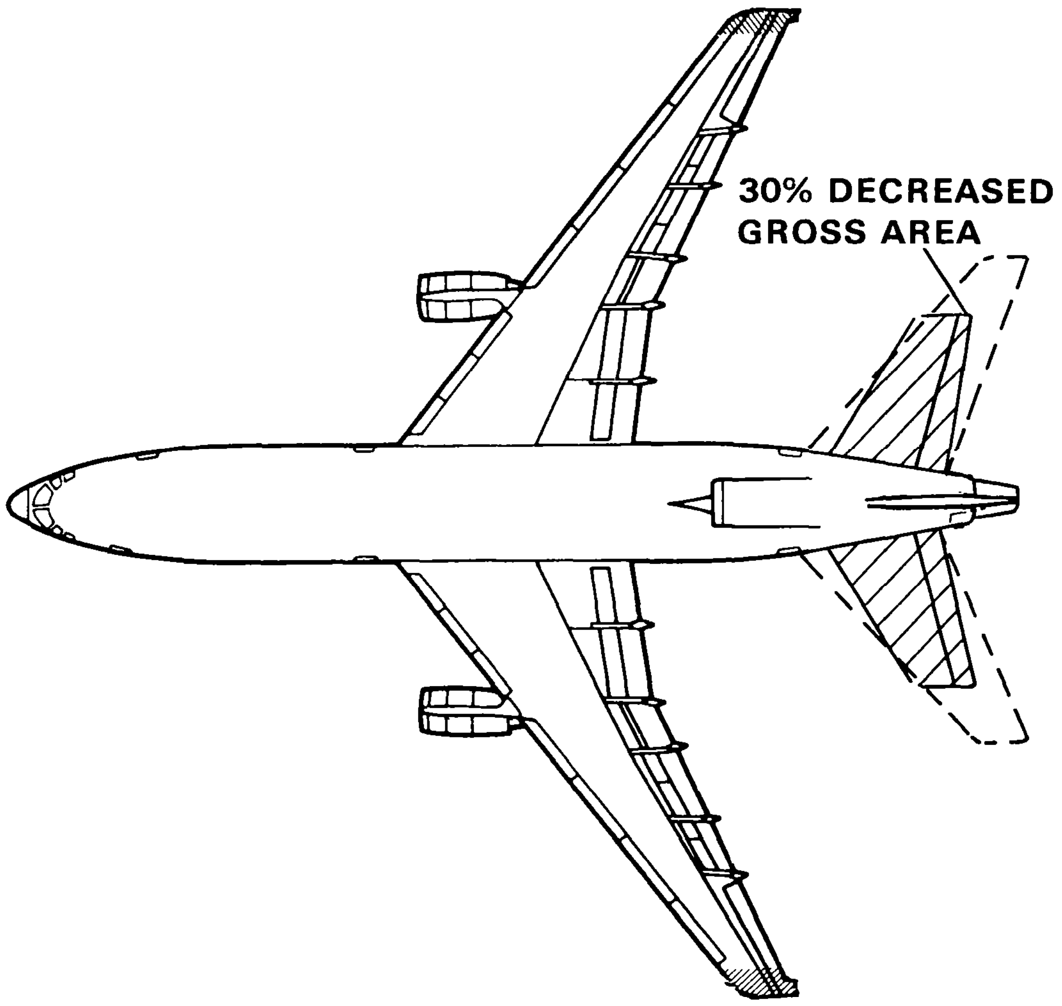
EVOLUTION OF CONTROL SYSTEMS

The control system components have undergone considerable change and refinement. Originally, simple mechanical linkages using cables, pulleys, and push rods were used. As hydraulic boost became popular, it became possible to improve the flying qualities in certain flight regimes by feeding back a sensed variable, such as yaw rate. The control system with simple augmentation still maintained full authority through mechanical connections between the pilot and the control surface. In the event of a failure of a control system component, the pilot still maintained control, but with reduced flying qualities. The current trend of fly-by-wire control systems requires redundancy of critical elements since there will no longer be mechanical connections between the pilot and control system as a backup. The concepts of fault tolerance, detection, and isolation are new areas of important research.



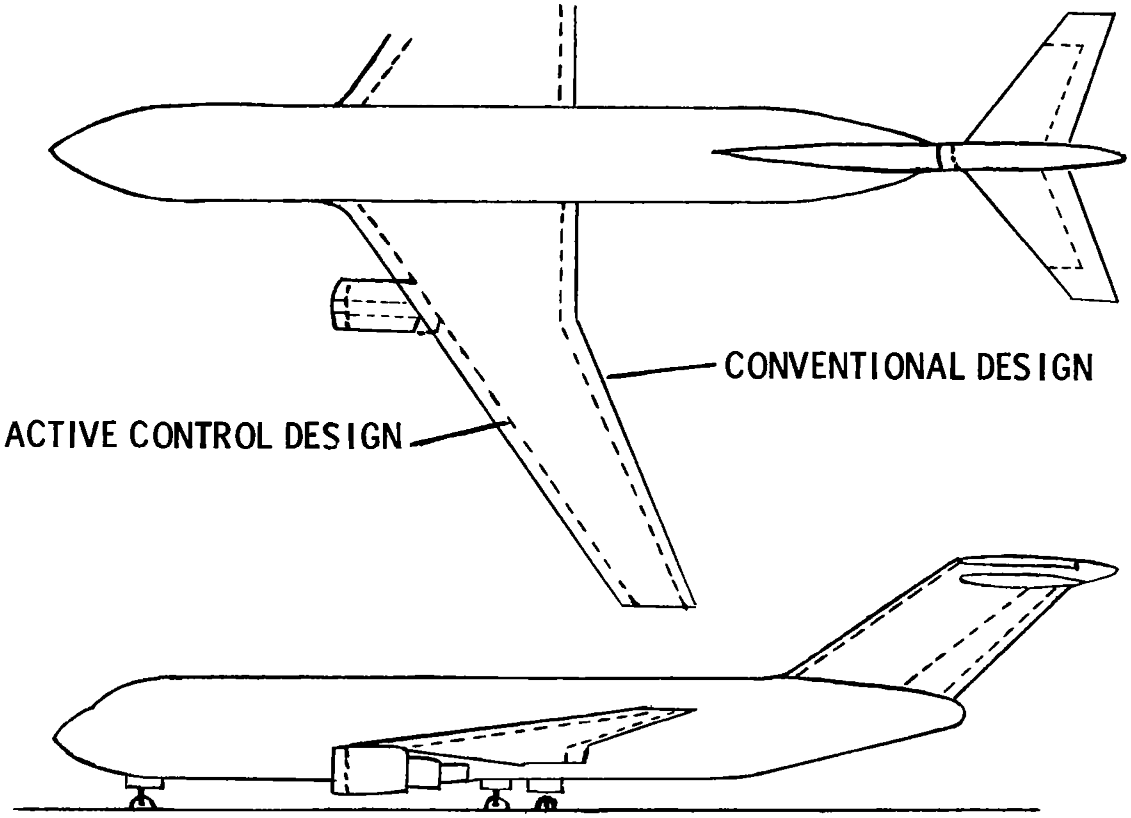
APPLICATION OF RSSAS TO A CURRENT TRANSPORT CONFIGURATION

Relaxed Static Stability Augmentation Systems (RSSAS) for transport configurations is one application of advanced control systems that may result in significant benefits. Immediate performance gains can usually be realized through a reduction in trim drag. Further gains can be achieved by resizing the horizontal tail due to a reduction in the stability constraint for the inherent aerodynamic stability of the aircraft. Good flying qualities will be achieved by the active control system. The reduction in tail area results in a decrease in aircraft operating weight and drag. All of these benefits yield fuel savings of 2 to 4 percent for most transport configurations.

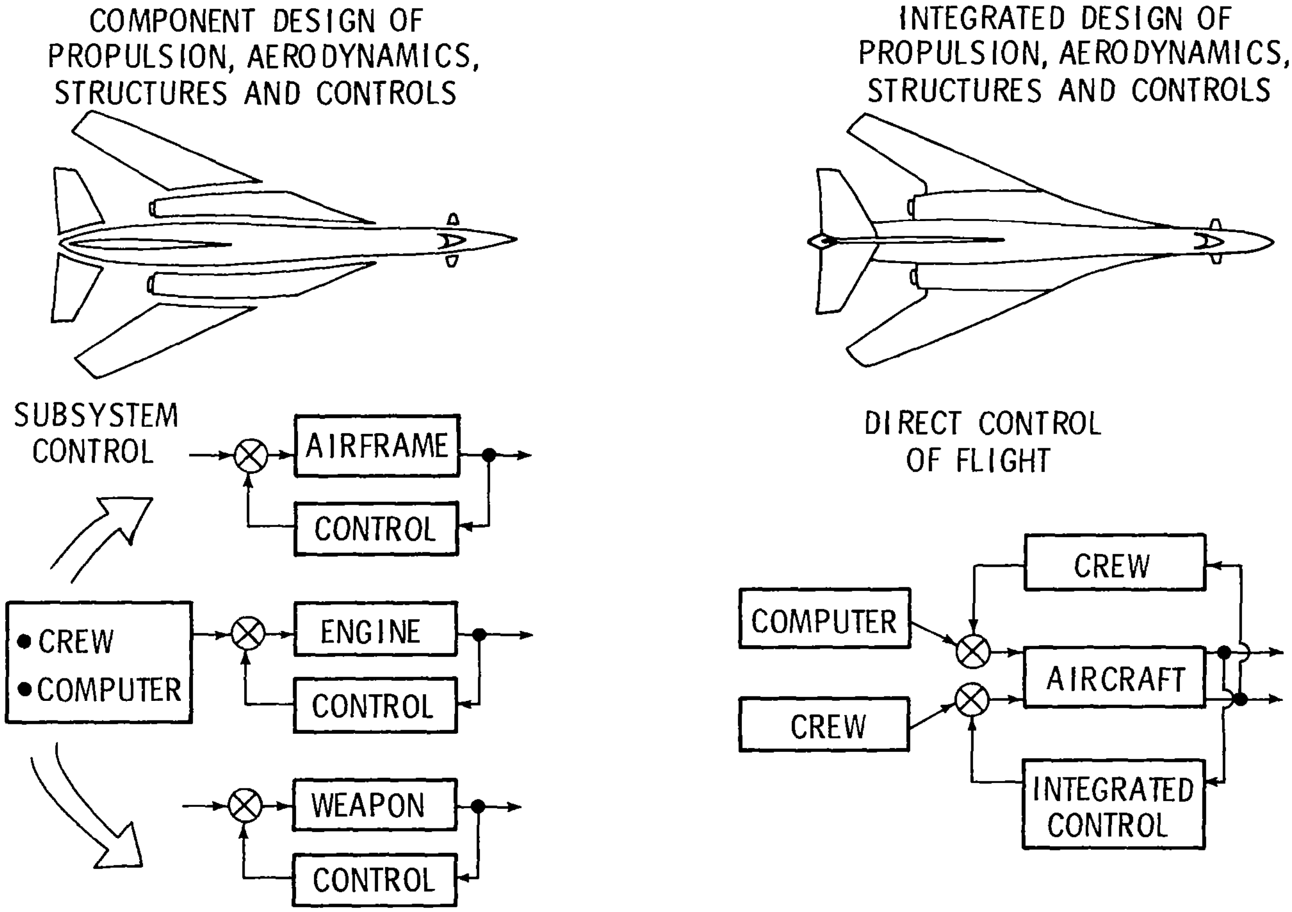


RESIZED TRANSPORT TO TAKE ADVANTAGE OF RSSAS

The greatest benefits of utilizing a RSSAS system can be achieved by introducing the concept at the conceptual design stages. A reduction in tail area results in weight and drag savings. Hence, the wing and engine can be resized, resulting in more weight savings. Additionally, the fuselage and landing gear structure can be redesigned for the lighter weight. In fact, after the airframe modifications, a further reduction in tail area may be possible, resulting in another round of changes. These benefits continue to cascade through the design but generally converge rapidly, resulting in a design which takes maximum, synergistic advantage of applying this new technology. If the concept is not introduced soon enough, the full benefits of RSSAS cannot be achieved. In the case of transport aircraft, fuel savings of 6 to 9 percent are possible.

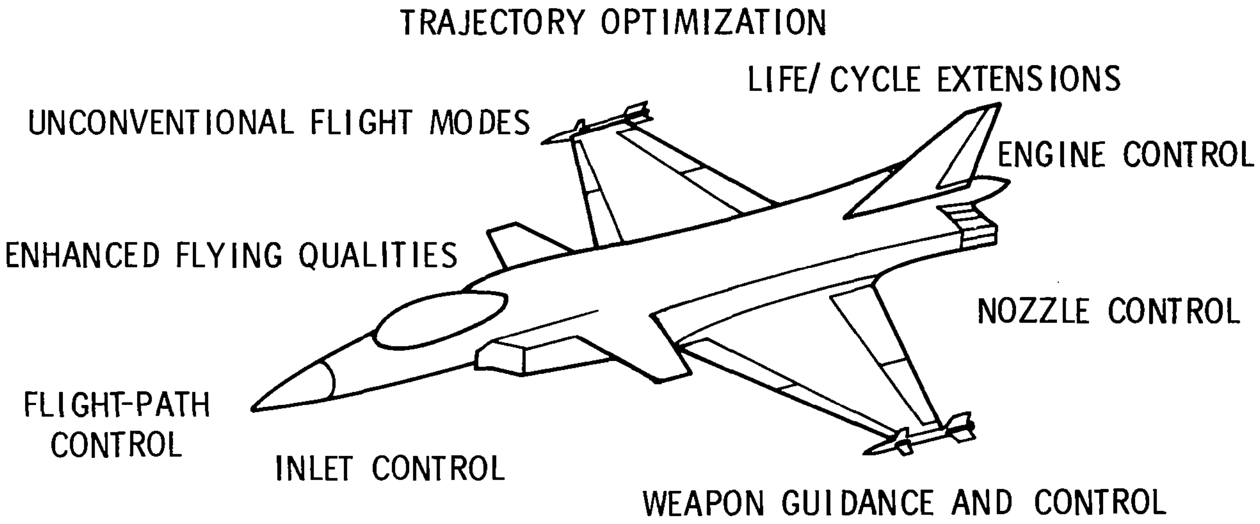


The actual integration of multiple decentralized control systems into a single centralized control system has also been a recent development which will result in augmented operational safety, performance, and capability as well as improved economy. In present practice, each component of the vehicle is designed independently. Certain advanced designs require control systems for various aspects, such as flying qualities, engine performance, structural damping, and weapon control. Each subsystem typically has an independent controller which is directed by the crew or flight management computer. It is conceivable that independent controllers could work in harmony; but, it is just as likely that they will conflict with each other. A preferred approach is to integrate all the controls and design each subsystem controller simultaneously. Such a system will tend to work in harmony in response to crew or computer commands.



FULL POTENTIAL OF INTEGRATED USE OF CONTROLS

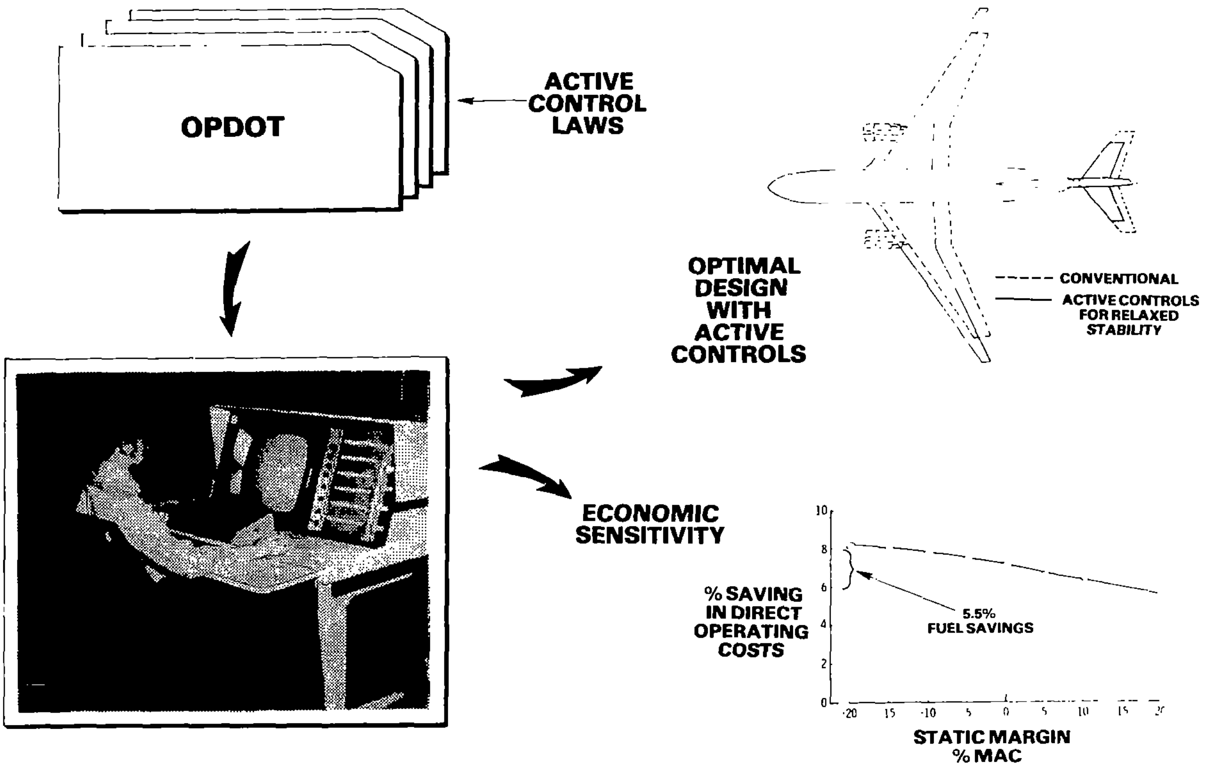
Once the use of advanced integrated controls has been hypothesized, there are many avenues that can be explored. Modern control theory allows the use of multiple effectors allowing such things as wing warping, rolling tails, spoilers, leading-edge devices, and thrust vectoring for control and performance enhancements. Unconventional flight modes, such as target alignment independent of flight path or side force excursions, can then be contemplated. All of these functions cannot be properly used if a separate controller is designed for each. Instead, a total integrated control system design approach should be used to minimize the conflicts and optimize the overall performance.



CONFIGURATION BENEFITS

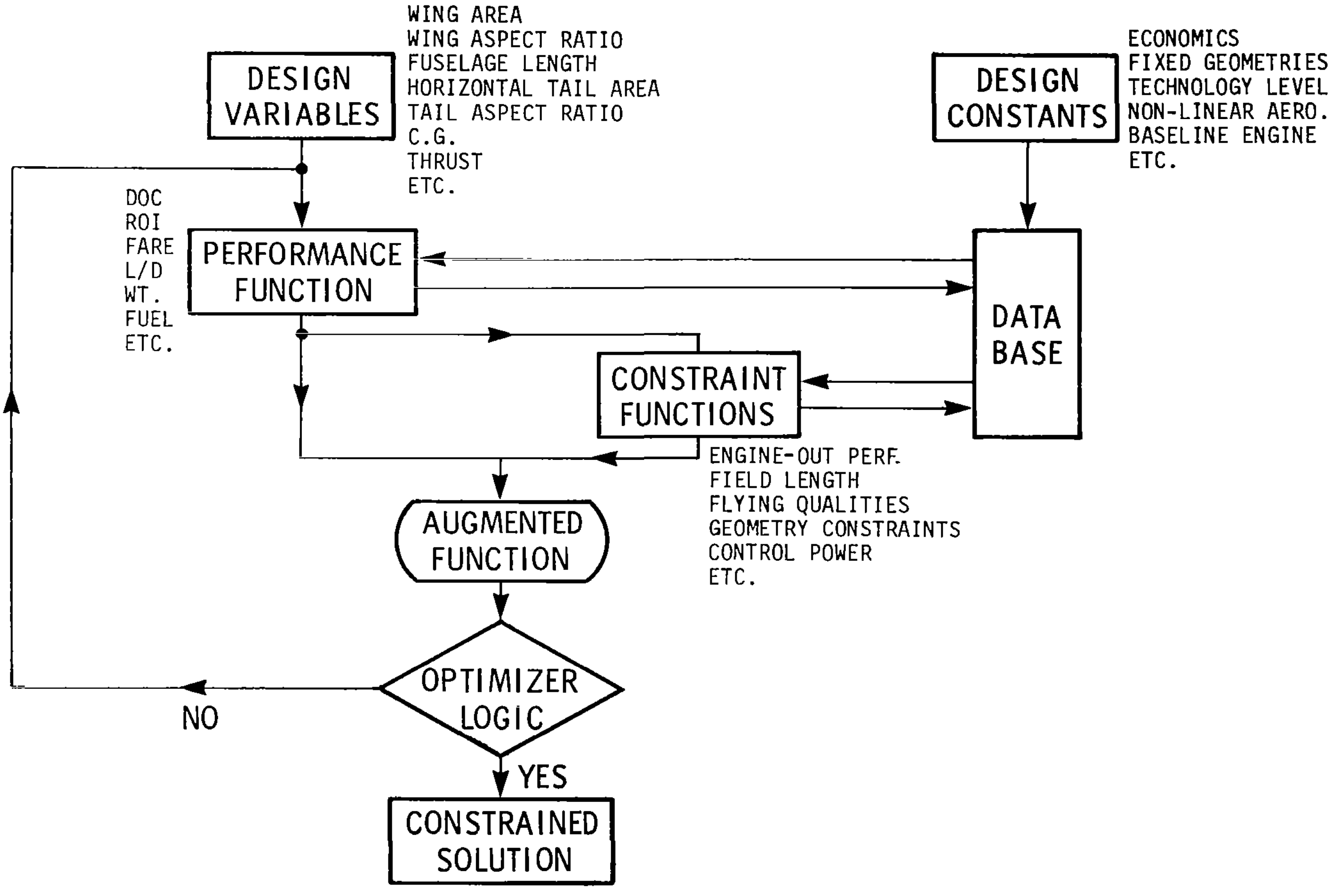
OPTIMUM PRELIMINARY DESIGN OF TRANSPORTS

OPDOT (Optimum Preliminary Design of Transports) is a computer program developed at NASA Langley Research Center for evaluating the impact of new controls technologies upon transport aircraft (see reference 1). It provides the capability to look at configurations which have been resized to take advantage of active controls and provide an indication of economic sensitivity to its use or the requisite assumptions. Although this tool returns a conceptual design configuration as its output, it does not have the accuracy, in absolute terms, to yield satisfactory point designs for immediate use by aircraft manufacturers. However, the relative accuracy of comparing generated configurations while varying technology assumptions has been demonstrated to be highly reliable making OPDOT a useful tool for ascertaining the synergistic benefits of active controls, composite structures, improved engine efficiencies, and other advanced technology developments.



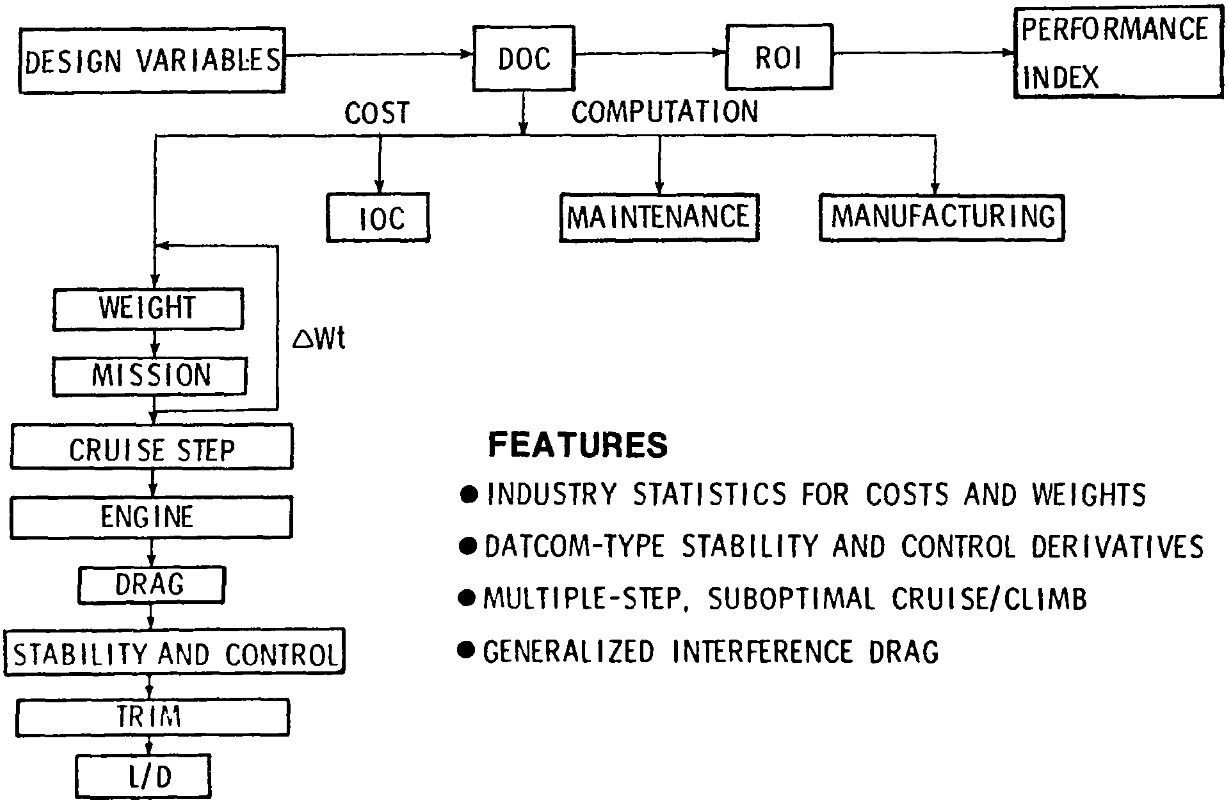
OPTIMAL DESIGN METHODOLOGY

The approach that is used by OPDOT is direct numerical optimization of an economic performance index. A set of independent design variables is iterated given a set of design constants and data. The design variables include wing geometry, tail geometry, fuselage size, engine size, etc. This iteration continues until the optimum performance index is found which satisfies all the constraint functions. The analyst interacts with OPDOT by varying the input parameters to the contraint functions or to the design constants. The optimization of aircraft geometry features is equivalent to finding the ideal aircraft size, but with more degrees of freedom than classical design procedures will allow.



PERFORMANCE FUNCTION FLOW DIAGRAM

The performance index in OPDOT is computed by having a candidate configuration "fly" an entire mission while satisfying reserve fuel requirements. Industry statistics are used for estimating weights and costs. The stability and control analysis is similar to Datcom-type capabilities, and the program computes the interference drag in a general way, making OPDOT sensitive to tail sizing considerations. The flight profile is a multiple-step model of a suboptimal cruise/climb for optimum fuel efficiency. The program is fairly flexible to use and has graphics output to illustrate each configuration.

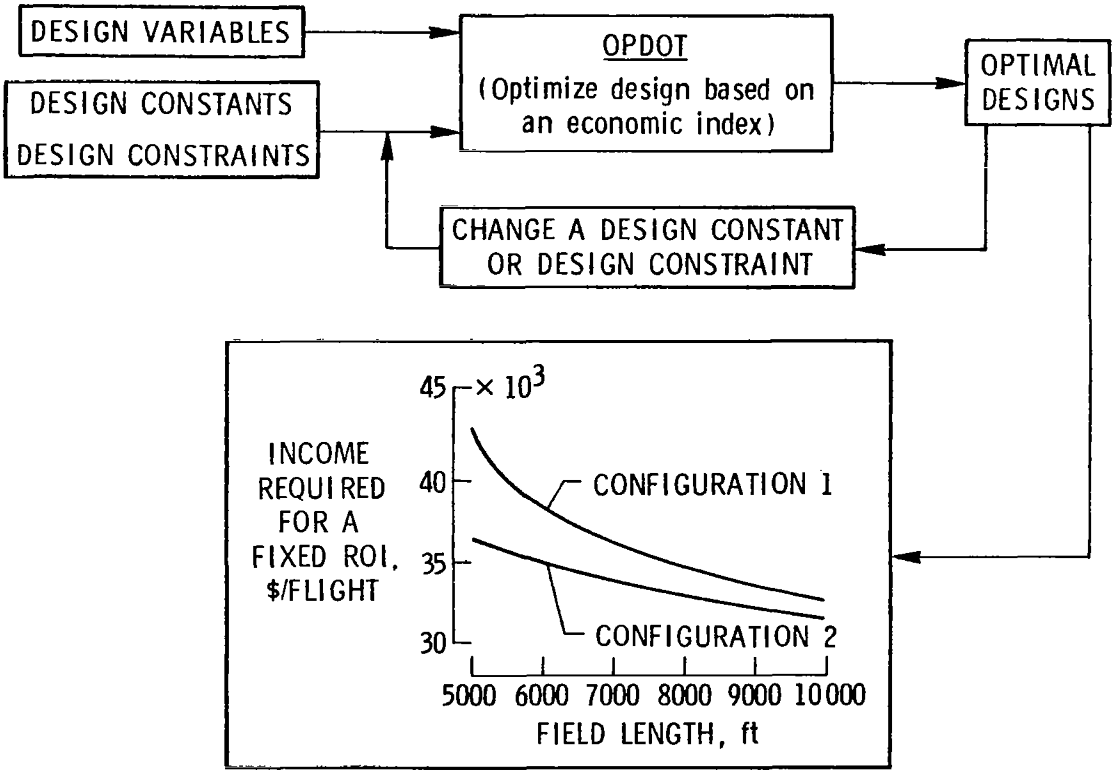


FEATURES

- INDUSTRY STATISTICS FOR COSTS AND WEIGHTS
- DATCOM-TYPE STABILITY AND CONTROL DERIVATIVES
- MULTIPLE-STEP, SUBOPTIMAL CRUISE/CLIMB
- GENERALIZED INTERFERENCE DRAG

METHODOLOGY FOR CONDUCTING SENSITIVITY STUDIES

A study is performed by inputting a set of problem parameters and selecting an initial set of independent design variables. OPDOT finds a solution, and that configuration is saved for later comparison. The analyst then systematically varies a design constant or constraint function, and each optimum design is stored. Then a locus of optimum designs can be plotted as a function of the parameter in question. This plot can be used to determine the sensitivity of a design to applying a new technology, for example, and each point includes the maximum synergistic benefits available for the set of inputs specified.



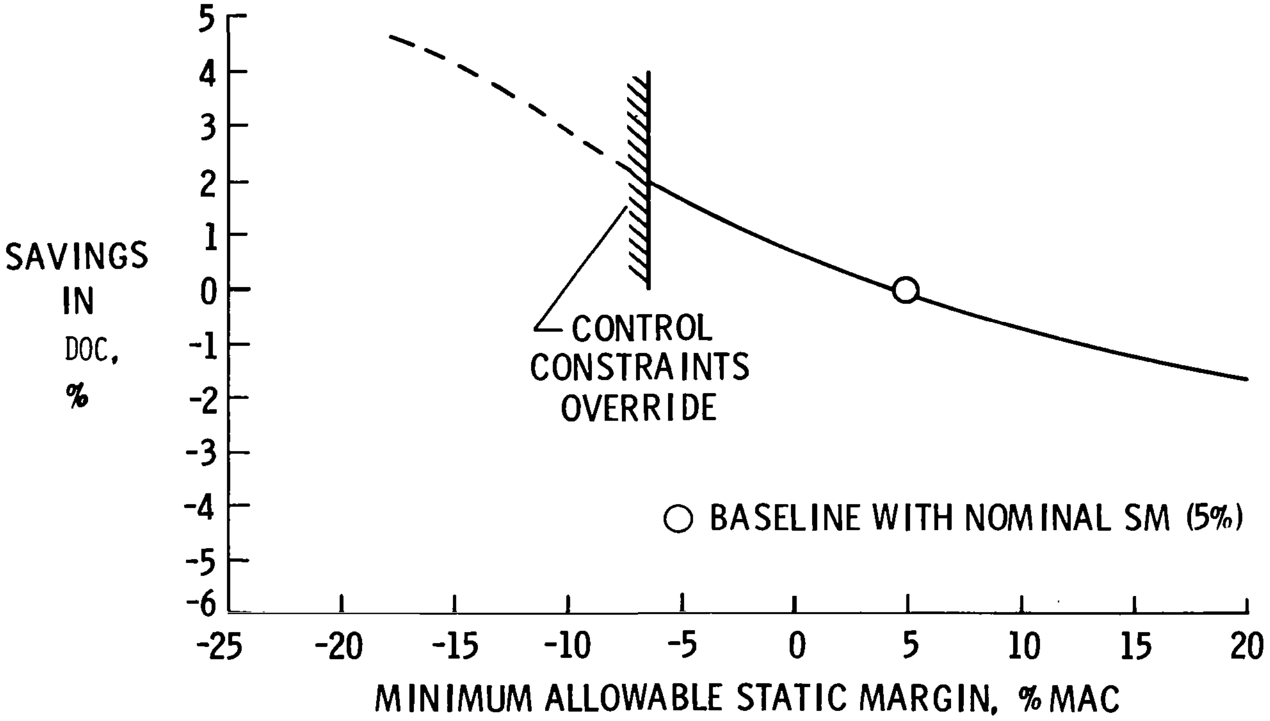
FLYING QUALITIES STUDY

One study that was made with OPDOT (references 2,3) was the evaluation of the impact of minimum acceptable flying qualities upon aircraft design. This is the prime factor which influences aircraft design when RSSAS systems are considered. It is assumed that an RSSAS system will augment the flying qualities up to more than acceptable levels, but provisions must be made in the event the autopilot/augmentation system fails. Transport aircraft will generally have mechanical backups, so they should have sufficient unaugmented stability to assure the flight can be completed after a set of failures. Clearly these requirements, in effect, specify the inherent aerodynamic stability characteristics of the configuration. OPDOT will give the designer and regulators economic sensitivities to these criteria, enabling a proper compromise between safety and economy to be made. During the course of this study, it was found that many of the criteria being considered for unaugmented flying qualities of transports with RSSAS were inadequate or inappropriate for specifying airplane design parameters.

- LEVEL OF UNAUGMENTED FLYING QUALITIES DETERMINES INHERENT STABILITY CHARACTERISTICS
- ECONOMIC SENSITIVITIES FOR THESE CRITERIA WERE FOUND
- MANY CRITERIA WERE INADEQUATE FOR PROPERLY SPECIFYING THE UNAUGMENTED FLYING QUALITIES

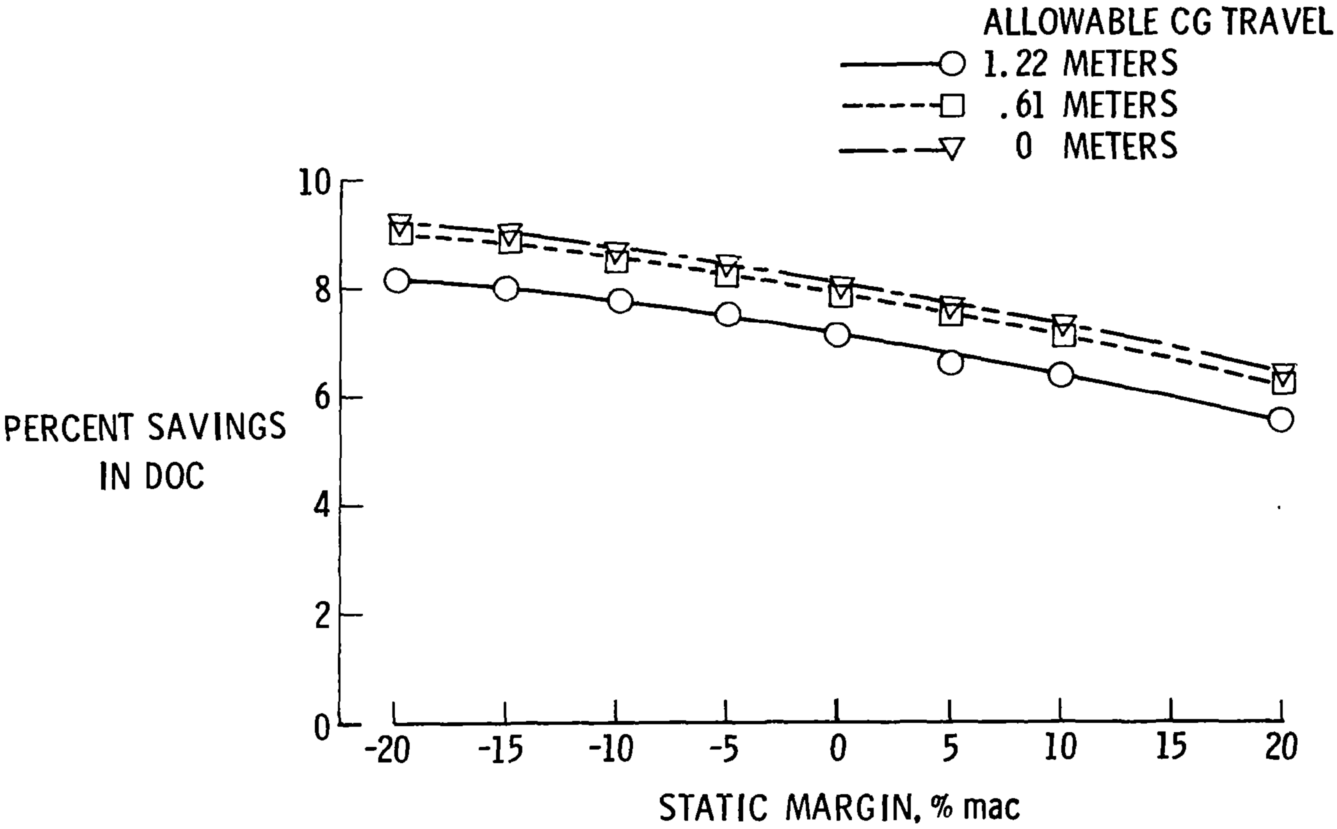
IMPACT OF STATIC MARGIN

A study was made considering the impact of relaxing the static stability requirement for transport aircraft. A locus of optimum designs is plotted. For the configuration being considered, a savings of 2.5 percent in direct operating cost is possible when compared to a baseline configuration with 5-percent static margin. This corresponds to a fuel savings of 6 percent. At a certain point, in this case at -7 percent static margin, reducing the static stability constraint yields no further improvements. This is because the control constraints (typically nose-gear unstick during takeoff) override the tendency to make the tail smaller. A certain minimum size tail is required for control, and the center-of-gravity cannot be moved any further aft without sacrificing nose gear steering traction.



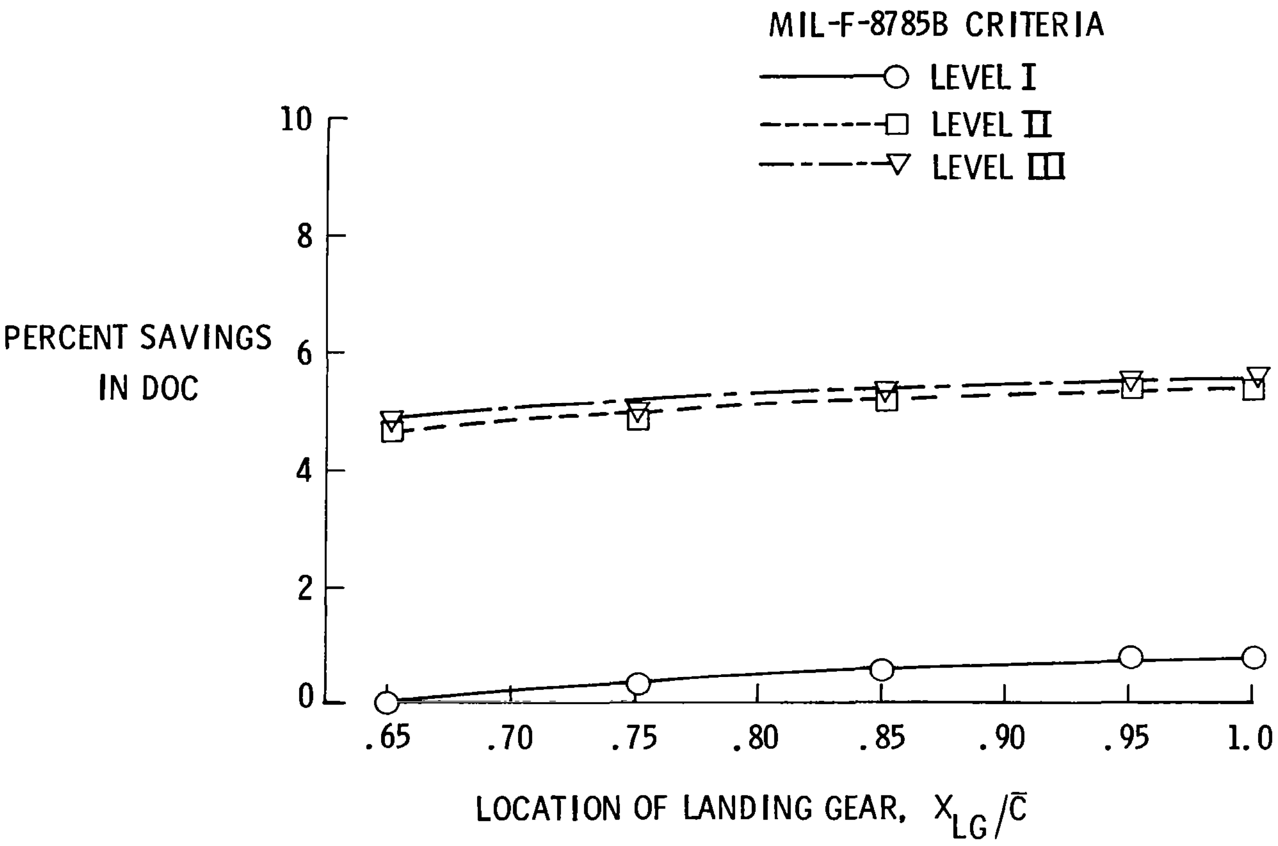
IMPACT OF LOADABILITY UPON DOC

Implied in the static margin sensitivity study was a range of allowed center-of-gravity travel. The control constraints are usually critical on the forward c.g. limit, and the stability constraints are usually critical on the aft c.g. limit. Reducing this range results in savings for all static margins under consideration. However, most benefits are achieved during the first 50 percent of reduction, indicating that if more careful center-of-gravity control is possible, a fuel savings of 2 percent or more is possible.



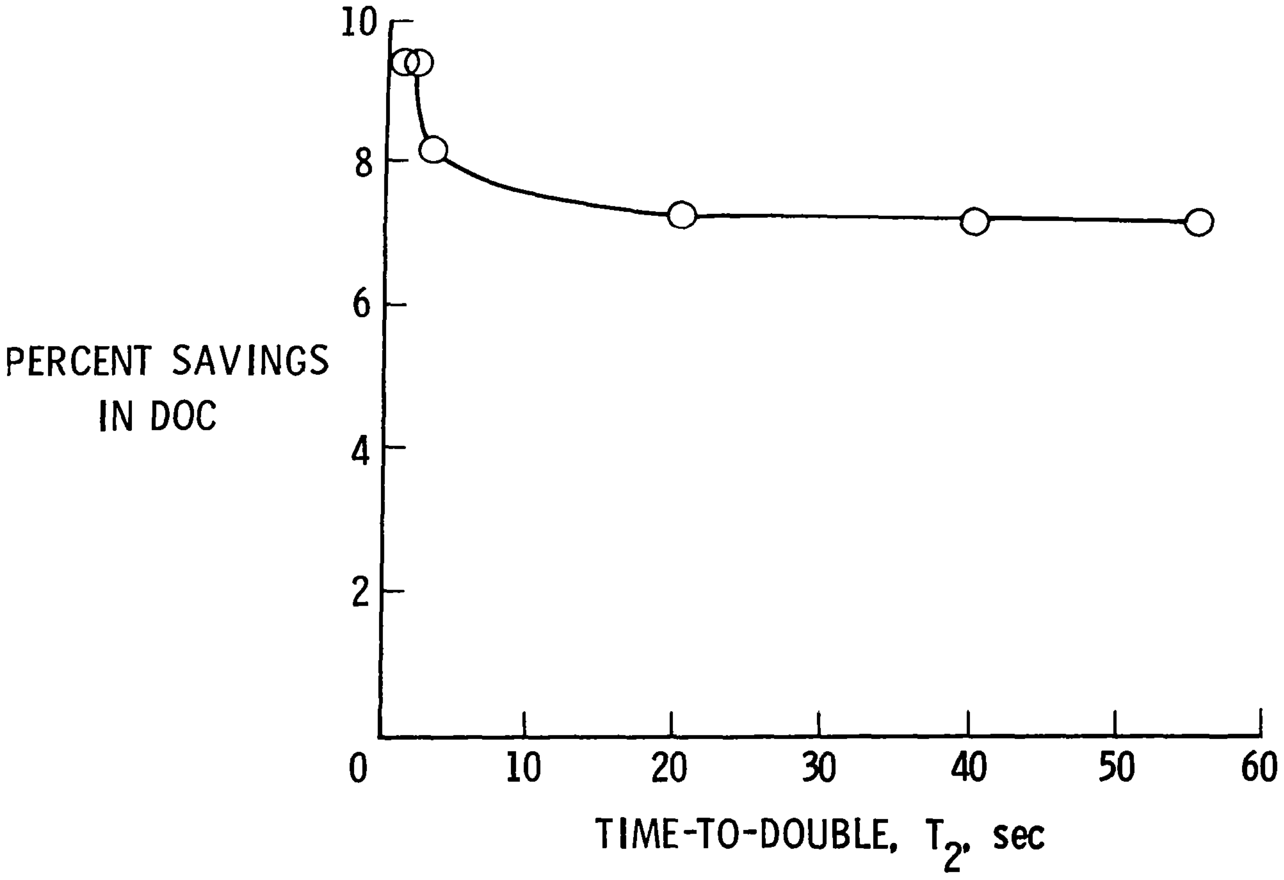
IMPACT OF LANDING GEAR LOCATION UPON DOC

Also implied in the static margin study was an aft limit for placing the landing gear. Studies have shown that the maximum aft placement for transport aircraft, where the gear and wing are collocated for structural efficiency, is about 65 percent of the mean aerodynamic chord. This is a critical constraint for RSSAS aircraft since it limits how far aft the center of gravity can travel before traction for nose gear steering is lost. Savings of nearly 1 percent in direct operating cost are possible if the gear could be located further aft without structural weight penalty. This corresponds to a fuel savings of over 2 percent.



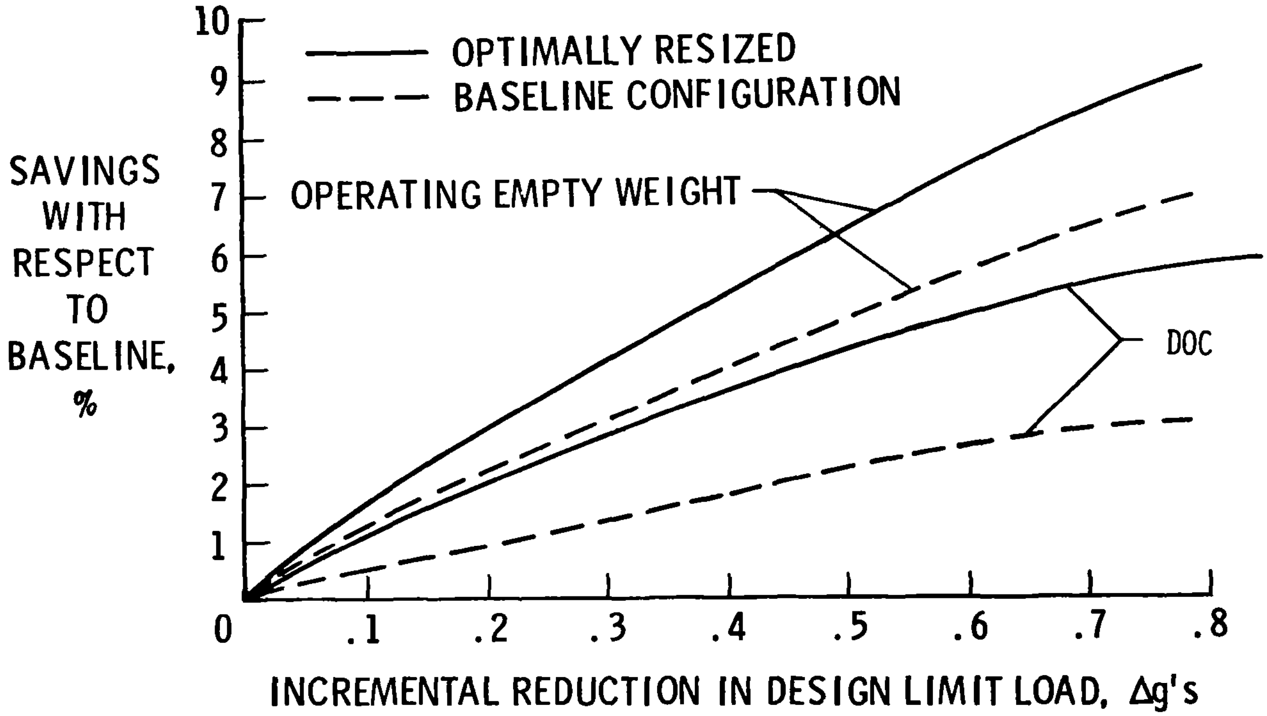
DOC SAVINGS VERSUS TIME-TO-DOUBLE

Another unaugmented flying qualities criterion that may be of interest is time-to-double amplitude. This plot illustrates the possible importance of economic sensitivity to a proposed criteria. If a designer or regulator is considering applying a constraint of 30 or 40 seconds, it is easy to see that the economic benefits of relaxing the constraint from 30 to 40 seconds is of little economic consequence. However, the opposite is true if considering an arbitrary boundary ranging between 2 and 6 seconds. The economic sensitivity information should be used before establishing the flight qualities criteria boundary since it significantly impacts the aircraft design.



IMPACT OF LOAD ALLEVIATION

Gust load alleviation and maneuver load alleviation are active controls concepts that have potential economic payoff. Utilization of these technologies impacts the design because the structure could be designed to a lower limit load factor resulting in a weight savings. Plotted is the savings in empty weight and direct operating cost for incremental reduction in limit load factor. The dotted line just reflects benefits of the lighter structure for the baseline configuration. The solid line includes resizing the airframe to take advantage of the weight savings from active controls.



RESEARCH USING OPDOT

Other studies have been performed using OPDOT, including the investigation of the relative benefits of applying general technology improvements to transports and the evaluation of required economic and mission assumptions. Recently, a study was completed which determined the economic viability of canard transports when compared to conventional aft tail configurations. Future studies planned include the completion of vectored thrust integration for transports; multi-body and multi-surface configuration with canard, wing, and aft tail evaluation; and commuter transport technology requirements.

OTHER STUDIES

- RANKING OF OTHER GENERIC TECHNOLOGY IMPROVEMENTS
  (REFS. 4,5)
- EVALUATION OF ECONOMIC AND MISSION ASSUMPTION
  (REF. 5)
- DETERMINATION OF ECONOMIC VIABILITY OF CANARD TRANSPORTS
  (REF. 6)

FUTURE STUDIES

- COMPLETION OF VECTORED THRUST STUDIES
- MULTI-BODY AND MULTI-SURFACE TRANSPORT EVALUATION
- STUDY COMMUTER TRANSPORT TECHNOLOGY REQUIREMENTS
- EXTEND PROGRAM TO OTHER AIRCRAFT TYPES

SUMMARY

The integration of controls early in the design process is important because the implication of unaugmented flying qualities during control system failures impacts the aerodynamic design; because it is a requisite for the proposed technology improvements to achieve their full, synergistic potential; and, because flight test expense can be saved. Adjustments to the control laws after an advanced technology prototype has been built is no longer an easy proposition. Hence, it has become increasingly important to include control technologist and design considerations during conceptual design. In this discussion, a computer program developed at NASA Langley was described which utilizes optimization techniques to evaluate economic sensitivities of applying new technologies at the preliminary design level of transport aircraft.

- IT IS BENEFICIAL TO INTEGRATE CONTROLS CONSIDERATIONS INTO BEGINNING OF DESIGN PROCESS

    CONTROL SYSTEM AND FAILURE MODE ASSUMPTIONS IMPACT INHERENT AERODYNAMIC DESIGN

    FULL POTENTIAL OF ALL TECHNOLOGIES CAN BE REALIZED

    FLIGHT TEST EXPENSE WITH RESPECT TO FLYING QUALITIES CAN BE SAVED

- A TOOL USING OPTIMIZATION TECHNIQUES HAS BEEN DEVELOPED FOR TRANSPORT AIRCRAFT

REFERENCES

1. Sliwa, Steven M.; and Arbuckle, P. Douglas: OPDOT: A Computer Program for the Optimum Preliminary Design of a Transport Airplane. NASA TM-81857, 1980.

2. Sliwa, Steven M.: Impact of Longitudinal Flying Qualities Upon the Design of a Transport With Active Controls. AIAA Paper No. 80-1570, Aug. 1980.

3. Sliwa, Steven M.: Economic Evaluation of Flying-Qualities Design Criteria for a Transport Configured With Relaxed Static Stability. NASA TP-1760, 1980.

4. Sliwa, Steven M.: Sensitivity of the Optimal Design Process to Design Constraints and Performance Index for a Transport Airplane. AIAA Paper No. 80-1895, Aug. 1980.

5. Sliwa, Steven M.: Use of Constrained Optimization in the Conceptual Design of a Medium-Range Subsonic Transport. NASA TP-1762, December, 1980.

6. Arbuckle, P. Douglas; and Sliwa, Steven M.: Parametric Study of Critical Constraints for a Canard Configured Medium Range Transport Using Conceptual Design Optimization. AIAA Paper No. 83-2141, Aug. 1983.