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EXPERIENCES PERFORMING CONCEPTUAL DESIGN OPTIMIZATION OF TRANSPORT AIRCRAFT

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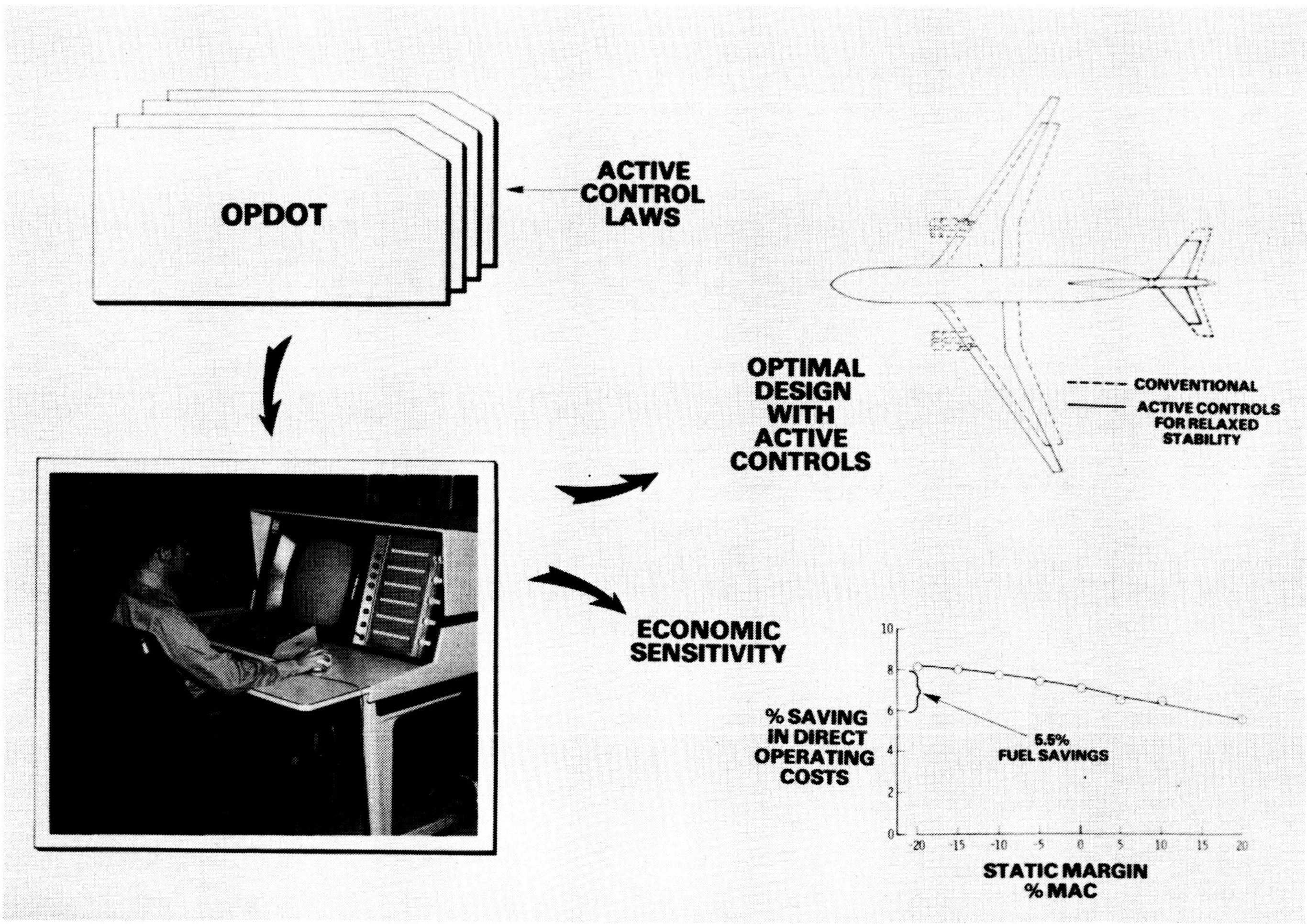
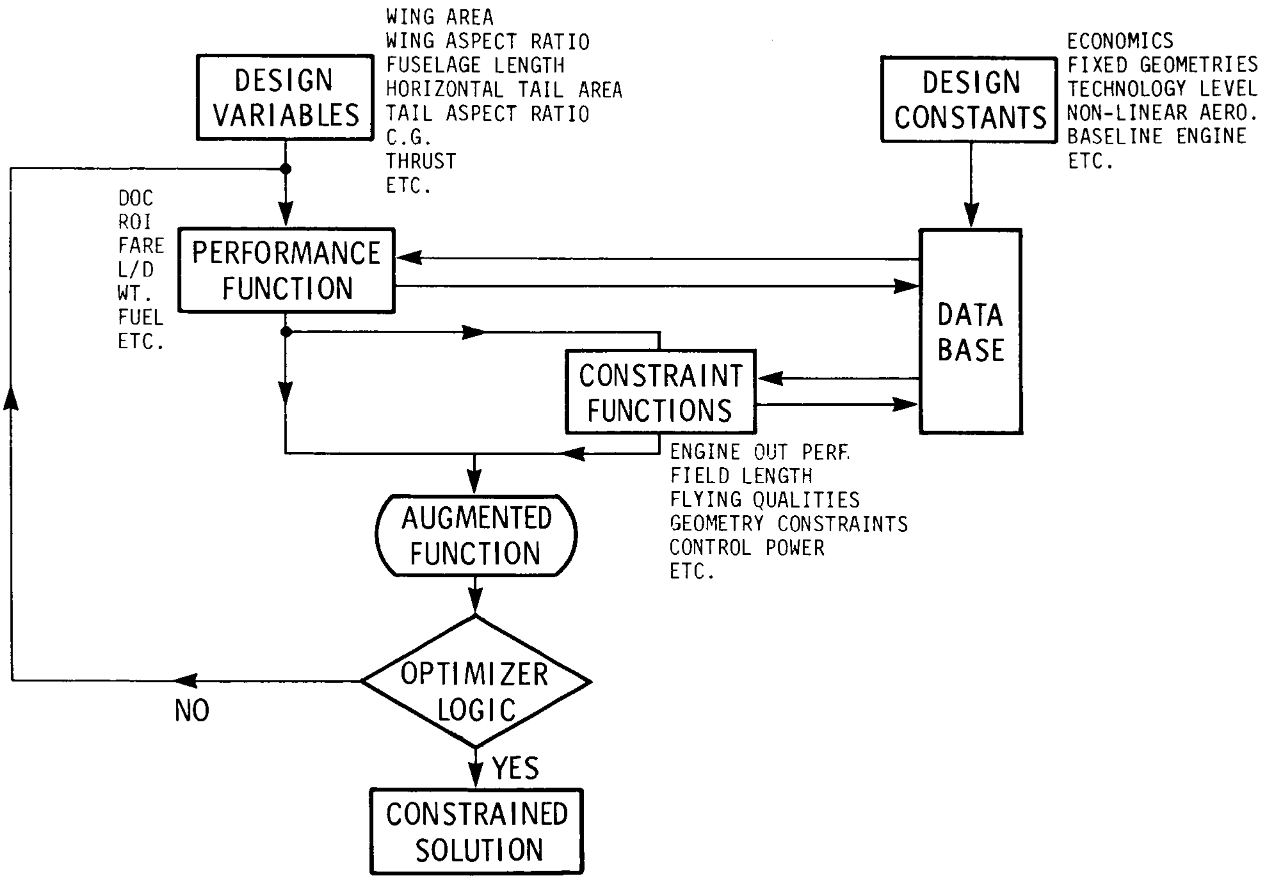
OPTIMUM PRELIMINARY DESIGN OF TRANSPORTS

OPDOT (Optimum Preliminary Design of Transports) is a computer program developed at NASA Langley Research Center for evaluating the impact of new technologies upon transport aircraft (Ref. 1). For example, 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. 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 OPDOT-generated configurations while varying technological assumptions has been demonstrated to be highly reliable. Hence, OPDOT is a useful tool for ascertaining the synergistic benefits of active controls, composite structures, improved engine efficiencies and other advanced technological developments.



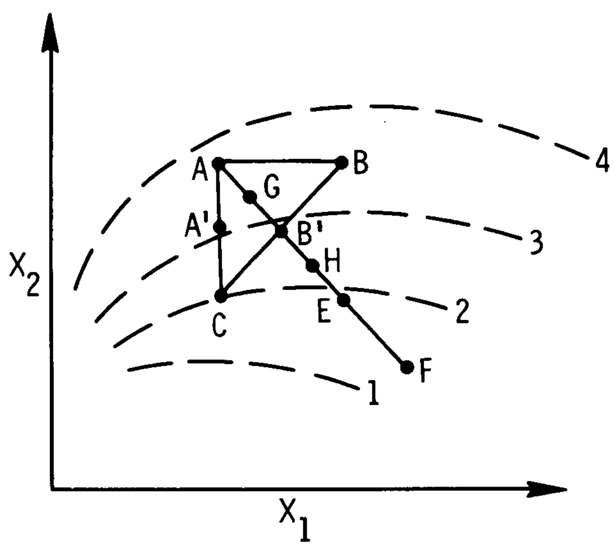
OPTIMAL DESIGN METHODOLOGY

The approach used by OPDOT is a 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, and engine size. 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 either the constraint functions or the design constants. Note that the optimization of aircraft geometry parameters is equivalent to finding the ideal aircraft size, but with more degrees of freedom than classical design procedures will allow.



NELDER-MEAD SIMPLEX PROCEDURE

Numerical optimization logic has been the focus of research in many disciplines for some time. For OPDOT, an algorithm was desired that would not require the constant supervision of the designer. A variety of gradient methods applicable to aircraft design, as well as a feasible direction/search method coupled with a gradient method for the final stage, were considered. But studies indicated that most methods suffered from numerical difficulties when analytical equations were not available to provide gradients, as well as initialization problems when the number of constraints was large with respect to the number of design variables. To overcome these difficulties, a direct sequential search simplex algorithm (the Nelder-Mead simplex procedure, Refs. 2 and 3) was utilized. This procedure is characterized by its adaptive nature, which enables the simplex to either reflect, extend, contract, or shrink to conform to the properties of the optimized function. Further, unlike most optimization procedures, this procedure approaches the optimum by moving away from "bad" values of the objective function, as opposed to trying to move directly towards the optimum. The most appealing features of the procedure from the designer's point of view are its reliability and its robust convergence (except in regions of the design variables with low gradients of the performance index).

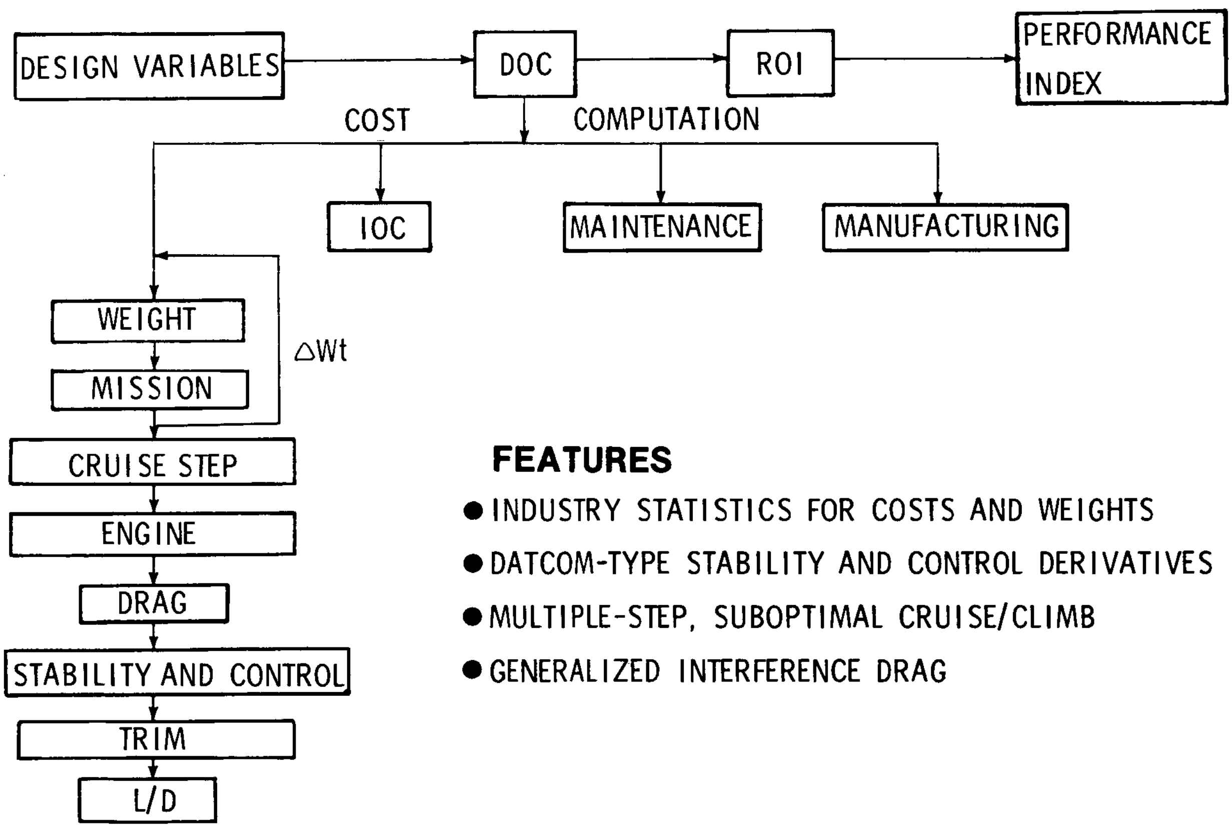


CHARACTERISTICS:

- DIRECT NUMERICAL PROCEDURE REQUIRING NO GRADIENTS
- MINIMUM APPROACHED BY MOVING AWAY FROM HIGH VALUES OF FUNCTION
- EXTREMELY RELIABLE, REQUIRING LITTLE "FINE-TUNING"
- ROBUST IN TERMS OF CONVERGENCE

PERFORMANCE FUNCTION FLOW DIAGRAM

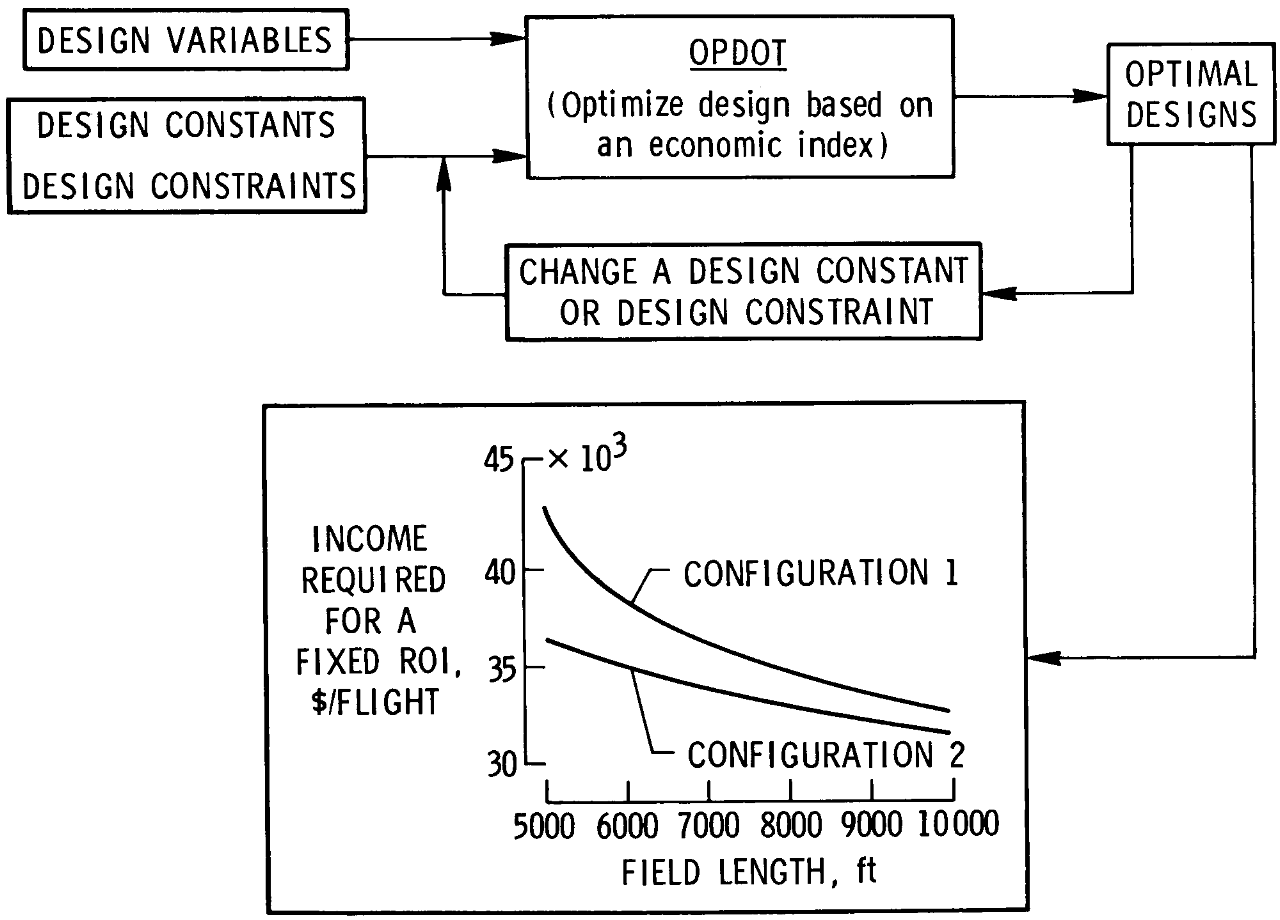
The performance index in OPDOT is computed by having a candidate configuration "fly" an entire mission while satisfying reserve fuel requirements. Industry statistics are used for estimating weights and costs. The stability and control analysis used is similar to Datcom-type capabilities and the program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



FEATURES

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

A sensitivity 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 saves each optimum design. A locus of these optimum designs can then be plotted as a function of the parameter in question. This plot is used to illustrate the sensitivity of a design to the application of a new technology, with each point representing a transport design which includes the maximum synergistic benefits available for the set of inputs specified.



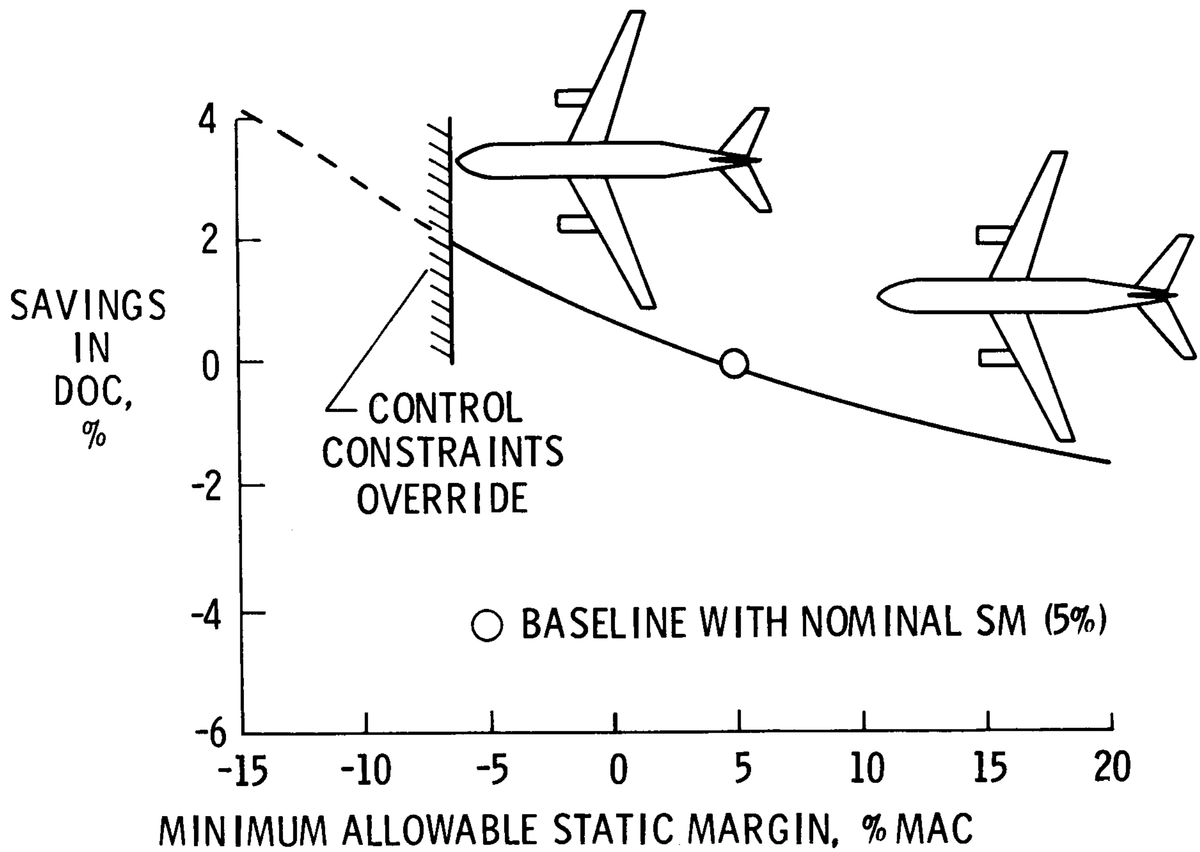
FLYING QUALITIES STUDY

One study that was made using OPDOT (Refs. 4,5) 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 back-ups, so a given configuration should have sufficient unaugmented stability to ensure that a flight can be completed after a set of failures. Clearly the unaugmented stability requirements, in effect, specify the inherent aerodynamic stability characteristics of a configuration. OPDOT will give designers economic sensitivities to these criteria, enabling a proper compromise between safety and economy. It was found that many of the criteria being considered for unaugmented flying qualities of transports with RSSAS were either inadequate or inappropriate for specifying airplane design parameters.

- DEMONSTRATED USE OF CONSTRAINED OPTIMIZATION IN PRELIMINARY DESIGN
- RSSAS SHOULD YIELD ABOUT 1.5% SAVINGS IN DOC (3.5% FUEL SAVINGS)
- LONGITUDINAL FLYING QUALITIES DESIGN CRITERIA FOR UNAUGMENTED TRANSPORTS NEEDS FURTHER RESEARCH

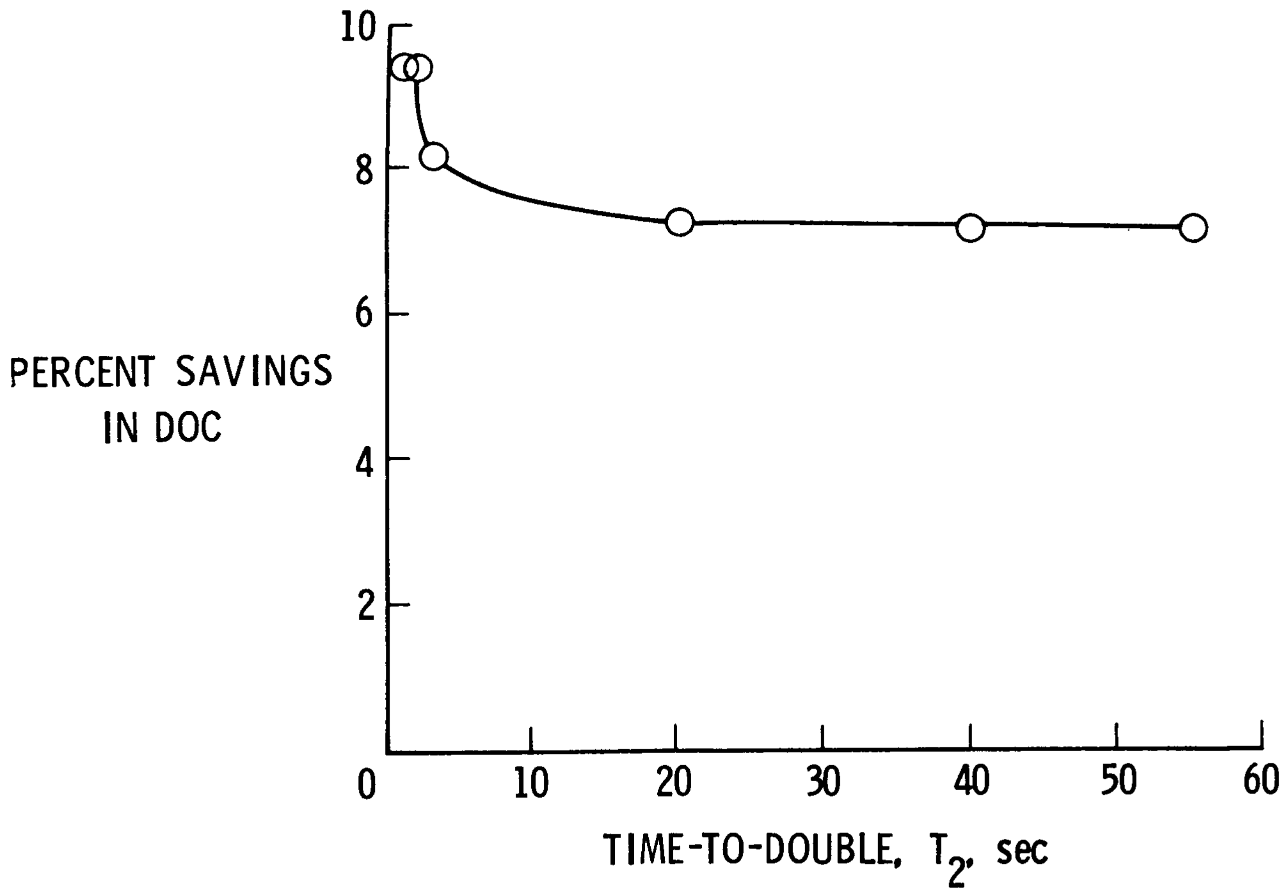
IMPACT OF STATIC MARGIN

One design parameter considered in the flying qualities study was the impact of relaxing the natural static stability requirement for transport aircraft. A locus of optimum designs indicates that, 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 -7 percent static margin, reducing the static stability constraint yields no further improvements. This is because the control constraints (typically nose gear unstick during take-off) prevent the design from having a smaller horizontal stabilizer, since a minimum size tail is required for control and the center-of-gravity cannot be moved any further aft without sacrificing nose gear steering traction.



DOC SAVINGS VS. TIME-TO-DOUBLE

One unaugmented flying-qualities criterion of considerable interest is time-to-double amplitude. This plot illustrates the importance of economic sensitivity to a proposed criterion. If a designer is considering applying a constraint of 30 or 40 seconds, it is easy to see that arbitrarily relaxing the constraint from 30 to 40 seconds is of little economic consequence. However, the opposite is true when considering an arbitrary boundary ranging between 2 and 6 seconds. Economic sensitivity information should be considered before establishing the flying-qualities criteria since they significantly impact the aircraft design.



DESIGN STUDY

OPDOT was also used in a study (Refs. 6,7) evaluating the sensitivity of transport aircraft design to various design constraints and technology assumptions. During this study, the full benefits of resizing the design to take advantage of a new technology were demonstrated. Various performance indices were used to generate "optimal designs" in an effort to identify a robust and meaningful economic index. FARE (defined as the income required for a fixed return-on-investment) was chosen as the best performance index for use in this and future studies. The impacts (measured in FARE) of various mission, economic, production, and technological specifications upon transport design were evaluated. Sizable savings were possible with moderate enhancements in structural efficiency, fuel consumption, load alleviation, and maximum lift coefficient. Modest gains were observed with reductions in wing drag coefficient, pitching moments, and static margin.

- DEMONSTRATED THE BENEFITS FROM SYNERGISTIC RESIZING OF A TRANSPORT CONFIGURATION TO TAKE ADVANTAGE OF NEW TECHNOLOGIES OR NEW OPERATING ENVIRONMENTS
- EVALUATED THE OPTIMAL DESIGN SENSITIVITY TO SELECTION OF VARIOUS PERFORMANCE INDICES
- QUANTIFIED TRANSPORT AIRCRAFT DESIGN SENSITIVITIES TO VARIOUS OPERATIONAL AND TECHNICAL CONSTRAINTS

CANARD STUDY

OPDOT has also been used in studies to evaluate and compare various proposed transport configurations. One of these studies was a comparison of a canard configuration with a conventional aft-tail configuration (Ref. 8). This study was initiated in response to the growing debate concerning the merits of canards and their impact on design. OPDOT was used to provide the following preliminary analyses: identifying critical design constraints, quantifying their impact on the design, comparing them with critical design constraints for aft-tail transports, and comparing the relative mission performance of canard and aft-tail transports. The canard study identified an unusually high canard $C_{L_{max}}$ requirement and an unconventional main gear location (out of the wing box structure) as critical design parameters for a canard transport.

Various assumptions were made in this study which may or may not be realistic. Further research into implementation of high lift devices on control surfaces and into quantification of the weight and drag penalties associated with an unconventional main gear location is required.

Designing for unstable static margins has been proposed to improve canard transport designs, but it was shown that a greater incremental benefit would be achieved by applying that technology to an aft-tail configuration.

- IDENTIFIED CANARD $C_{L_{MAX}}$ AND MAIN LANDING GEAR LOCATION AS CRITICAL DESIGN CONSTRAINTS FOR CANARD TRANSPORTS
- IF NOMINAL VALUES OF THE IDENTIFIED CRITICAL CONSTRAINTS CAN BE ACHIEVED WITH LITTLE PENALTY, THEN CANARD TRANSPORTS MAY EXHIBIT BETTER ECONOMIC PERFORMANCE
- DESIGNING FOR UNSTABLE STATIC MARGINS BENEFITS CONVENTIONAL TRANSPORT DESIGNS MORE THAN CANARD TRANSPORT DESIGNS

TWIN-FUSELAGE STUDY

Among the ideas developed by NASA Langley researchers for improving transport efficiency is the proposed twin-fuselage transport configuration (Ref. 9). It is argued that the twin-fuselage configuration offers two key advantages over a comparable conventional configuration: a lighter, lower-drag fuselage per passenger, and a higher wing aspect ratio. However, twin-fuselage configurations introduce several new design problems that must be examined.

A study of twin-fuselage configurations using OPDOT was recently initiated, with a focus on obtaining quantitative economic and performance comparisons of twin-fuselage and conventional configurations as well as identifying key design parameters for the twin-fuselage transport. The preliminary results of the twin-fuselage configuration study show that a 250-passenger twin-fuselage transport is approximately 8 percent cheaper to operate than a comparable conventional transport. However, it is uncertain whether the statistical relationships used by OPDOT (especially for wing weight computations) remain valid for all of the twin-fuselage configurations studied. Typically, these configurations had wing aspect ratios of 11-12. Further, no consideration has been given to additional engineering, development, or certification costs that might be incurred by a twin-fuselage configuration. Even so, potential wing weight reductions show great promise and may determine the economic viability of typical twin-fuselage configurations. These potential wing weight reductions require more detailed study to firmly establish the advantage of a twin-fuselage configuration.

- A TWIN-FUSELAGE TRANSPORT MAY BE MORE ECONOMICAL THAN FUTURE CONVENTIONAL TRANSPORTS
- HYPOTHESIZED WING STRUCTURAL WEIGHT REDUCTIONS DUE TO TWIN-FUSELAGE CONCEPT SHOW PROMISE AND NEED FURTHER STUDY

LESSONS LEARNED

During the course of the studies presented in this report, it became apparent that it is necessary to have a reliable optimization algorithm. Many optimizations need to be performed for such trade studies, and they should require as little "fine-tuning" from the designer as possible. Performing airplane design with computer optimization techniques places a burden on the designer to properly constrain the problem. This requires the analyst to carefully consider the fundamental factors which determine an aircraft's configuration.

OPDOT is very effective at maximizing the synergistic economic benefits of utilizing a new technology, since it provides an opportunity to integrate a new technology early into the design process. Because the accuracy of certain weight and cost statistics is expected to be of the order of 10 percent, OPDOT is viewed as being most useful in comparing various calculated designs to illustrate relative benefits, rather than in predicting absolute cost or performance figures of point designs. The inherent sensitivity of applying new technologies, changing mission constraints, or varying economic assumptions is of prime interest to the designer anyway. Experience has shown that if a design has not been properly constrained, it will often either diverge or converge to an impractical solution. Analysts using OPDOT must skim the intermediate calculations to assure that each set of designs is feasible. Tools like OPDOT can increase the productivity and accuracy of designers, but experience is still needed to properly plan a study and interpret the results. This is especially true since the region of validity of the statistical data must be considered. OPDOT is best viewed as an interpolation tool as opposed to an extrapolation tool.

- USED RELIABLE DIRECT-SEARCH OPTIMIZATION ALGORITHM
- METHODICAL USE OF CONSTRAINTS REQUIRED
- VERY EFFECTIVE AT MAXIMIZING SYNERGISTIC BENEFITS OF APPLYING NEW TECHNOLOGIES
- PRIME USE IS FOR DETERMINING RELATIVE BENEFITS AS OPPOSED TO DETERMINING POINT DESIGN
- INTERMEDIATE RESULTS SHOULD BE REVIEWED BY KNOWLEDGEABLE DESIGNER FOR FEASIBILITY
- OPDOT IS MOST ACCURATE WHEN USED AS INTERPOLATION TOOL VERSUS EXTRAPOLATION TOOL

SUMMARY

Since the synergistic benefits of a new technology are often twice (or more) the benefits obtainable from "adding" a new technology to an existing design, the integration of new technologies or relaxed design constraints should occur early in the design process so that the maximum advantages may be obtained. A computer program (OPDOT) has been developed at NASA Langley which utilizes optimization techniques to evaluate economic sensitivities of applying new technologies at the preliminary design level for transport aircraft. In this presentation, results from studies conducted with OPDOT have been summarized to illustrate the benefits of this approach.

- IT IS ESSENTIAL TO INTEGRATE NEW TECHNOLOGY CONSIDERATIONS IN THE BEGINNING OF THE DESIGN PROCESS TO REALIZE FULL POTENTIAL BENEFITS
- DEVELOPED RESEARCH TOOL FOR COMPARING EFFECTS OF TECHNOLOGY AND OTHER CONSTRAINTS ON TRANSPORT SIZING AND ECONOMICS
- CONDUCTED STUDIES TO QUANTIFY THESE EFFECTS
- CONDUCTED STUDIES TO PROVIDE PRELIMINARY ANALYSES OF PROPOSED NEW TRANSPORT CONFIGURATIONS

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