NASA Technical Paper 1760

Economic Evaluation of Flying-Qualities Design Criteria for a Transport Configured With Relaxed Static Stability

Steven M. Sliwa

DECEMBER 1980

NASA

NASA Technical Paper 1760

Economic Evaluation of Flying-Qualities Design Criteria for a Transport Configured With Relaxed Static Stability

Steven M. Sliwa
Langley Research Center
Hampton, Virginia

NASA
National Aeronautics
and Space Administration

Scientific and Technical
Information Branch

1980

SUMMARY

An optimal design program with constrained parameter optimization has been shown to be useful in evaluating the impact of certain flying-qualities design assumptions and in determining the sensitivity to several related parameter variations. Transports optimally configured with relaxed static stability showed a potential savings in direct operating cost of 1.4 percent when compared with transports with conventional static margins. This corresponded to a fuel savings of 4.2 percent for the medium-range mission considered. Savings of nearly 1 percent in direct operating cost were also possible from utilizing half the nominal center-of-gravity range of travel and from allowing the landing gear to be structurally dislocated from the wing. Requiring transports to be able to take off with the stabilizer trimmed in the most adverse position was shown to penalize the aircraft over 4 percent in direct operating cost.

During the course of this study, it became obvious that there is a need for developing design criteria for the minimum flying qualities that are necessary for specifying the inherent stability and control characteristics of augmented transports. Most existing criteria did not have useful parameters for defining handling qualities of inherently unstable transports which rely upon augmentation systems. Furthermore, few flying-qualities data were available in terms of factors that would be useful for developing appropriate inherent longitudinal-handling-qualities design criteria for transports configured to take maximum advantage of relaxed-static-stability augmentation systems.

INTRODUCTION

Active controls technology in aircraft design involves the application of automatic control systems which augment either the rigid or flexible body dynamics of the aircraft. This is done to enhance either performance, structural efficiency, airframe lifetime, ride quality, or some other measure. Relaxed-static-stability augmentation systems (RSSAS) constitute an active controls concept that has already been successfully applied to fighter and supersonic transport configurations. Similarly, significant benefits are anticipated for subsonic commercial transports if the RSSAS concept could be applied (refs. 1 and 2). Utilization of RSSAS permits a more aft center-of-gravity position, which typically attenuates the required tail lift for trim, thereby reducing the induced drag of the tail. Stability reductions also permit smaller tail surfaces, which reduce wetted area drag and weight.

The benefits of applying RSSAS to transports were initially hypothesized by conceptually retrofitting current configurations (refs. 3 and 4). The performance gains were estimated by adjusting center of gravity and tail size to minimize weight and tail drag while satisfying flying-qualities and control-power requirements. This scheme provided rough approximations of the potential benefits, but fell short of documenting the full benefits which would be possible by applying RSSAS early in the design process. Currently, a program is underway to study the implications of minor configuration alterations at the preliminary design level which could enhance the application of active controls technology (ref. 5).

With respect to RSSAS, there are two major obstacles to hinder the realization of the maximum performance improvements. First, syntheses of the configurations under study are being heavily influenced by current hardware and, in reality, have only minor degrees of freedom in geometry. The designs are being optimized by classical engineering methods, which include intuition in achieving the proper balance between weight savings and performance improvements. It is assumed that the operating cost of the overall vehicle will then be optimized.

Secondly, the first assumption required when designing a transport with an RSSAS is the level of the aerodynamic or inherent stability contribution toward the fully augmented flying qualities. If it can be assumed that it is always possible to augment an airplane to the desired level of flying qualities, the unaugmented flying qualities impact the design principally through failure mode considerations. It is still unresolved, even philosophically, what level of flying qualities a transport should have in the event of control system failures (refs. 6 to 11). Design philosophies range from requiring excellent flying qualities to having marginally safe handling qualities for landing and even to allowing loss of the aircraft (requiring fail-safe reliability in the automatic control system).

The study reported herein utilized a direct constrained optimization procedure for the preliminary optimal design of transport aircraft for the purpose of identifying the full benefits of RSSAS. The aircraft geometry was optimally sized to yield the maximum obtainable improvements from RSSAS in terms of minimum direct operating cost per block hour. The flying-qualities and related constraints were systematically varied to identify the configuration sensitivity to these assumptions. This information (which was presented in condensed form in ref. 12) should allow both designers and those concerned with flight safety to appreciate the impact of choosing appropriate unaugmented longitudinal-flying-qualities criteria upon the design of transports configured with RSSAS.

SYMBOLS AND ABBREVIATIONS

AR	aspect ratio
$C_{A\$}$	airplane cost, 1979 dollars
C_D	drag coefficient, $\frac{D}{qS}$
$C_{D,o}$	total drag coefficient at zero lift
$C_{F\$}$	fuel cost per block hour, 1979 dollars
c.g.	center of gravity

C_L	lift coefficient, $\frac{L}{qS}$
$C_{L,o}$	design lift coefficient of the airfoil section representing the center of the drag bucket
$C_{M\$}$	maintenance cost per block hour, 1979 dollars
D	drag, N
DOC	direct operating cost per block hour, 1979 dollars
g	acceleration due to gravity, 9.8 m/sec^2
FARE	income per seat-kilometer required to generate a 15-percent ROI, 1979 dollars
IOC	indirect operating cost per block hour, 1979 dollars
L	lift, N
L/D	aerodynamic efficiency, C_L/C_D
ℓ_f	fuselage length, m
MAC	mean aerodynamic chord, m
MDOC	modified direct operating cost per block hour, 1979 dollars
$\overline{MDOC}$	modified direct operating cost per block hour for baseline configuration, 1979 dollars
n/α	steady-state normal acceleration change per unit change in angle of attack for an incremental longitudinal control deflection at constant airspeed, gravity units/radian
OPDOT	computer program, Optimal Preliminary Design of a Transport
P	savings in augmented direct operating cost, percent $P = \frac{\overline{MDOC} - MDOC}{\overline{MDOC}} \times 100$
PR	pilot rating
q	free-stream dynamic pressure, N/m^2
rms	root mean square with respect to mean

ROI	annual return on investment, percent
RSSAS	relaxed-static-stability augmentation systems
S	lifting surface area, $m^2 (A^2)$
T	installed thrust, N (lbf)
Wt	weight, N
X_{lg}/MAC	longitudinal landing gear position, fraction of the mean aerodynamic chord
ζ_{sp}	short-period damping ratio
ω_{sp}	short-period natural frequency, sec^{-1}

Subscripts:

e	empty
max	maximum
t	horizontal tail
to	take-off
tot	total
w	wing

PROCEDURE

Method of Calculation

The computer program used for performing the trade studies during the flying-qualities analysis was OPDOT, Optimal Preliminary Design of a Transport. A more complete description of this computer program is presented in reference 13. The optimization indicated in reference 13 was performed using a modification of the sequential simplex optimizer proposed in references 14 and 15. The nonlinear programming logic is shown in figure 1. A trigonometric function transformation (ref. 16) was utilized which automatically scaled the independent design variables iterated by the optimizer and applied constraints directly to the design variables. Nominal values for the independent design variables (wing area, wing aspect ratio, fuselage length, horizontal-tail area, horizontal-tail aspect ratio, installed thrust, and c.g. location) were assumed, and a set of design constants were input into the data base (table I). These constants were used to specify the mission, operating economics, nonvarying or simply scaled geometries, and some of the nonlinear aerodynamic terms. These inputs were held constant throughout this analysis unless explicitly stated otherwise.

The optimizer is a section of computer code which interacts with the data base, taking the current value of each design variable as input to generate a performance index. The performance index used as a figure-of-merit for this study was a modified direct operating cost per block hour (MDOC). This criterion, which was minimized by the optimizer within the constraint boundaries, involves the estimation of the cost performance from a simulated mission. A schematic for the logical flow of this section of computer code is shown in figure 2.

The mission profile was a multiple-step classical (ref. 17) approximation to an optimal fuel-efficient flight path. This path began with a climb to altitude within the maximum speed regulations, followed by a cruise-climb at maximum $C_L/C_D^{3/2}$ to maximize range factor, then a cruise-climb at maximum C_L/C_D, and finally a rapid descent to landing. The fuel usage of this profile has been shown to be within about 3 percent of a continuous optimally fuel-efficient flight path (ref. 18). Although this was not included in the cost relationships, the aircraft was sized to carry enough fuel to satisfy the reserve requirements. Since about 95 percent of the fuel burnoff is realized during the cruise-climb parts of the mission profile, the independent design variables and other design inputs will have the most impact on these portions of OPDOT's model of the transport operation.

The aircraft weight was estimated in an iterative fashion from the equations of references 17, 19, and 20. Although take-off weight is the summation of each of the estimated component weights as well as both the payload and fuel, the take-off weight was required by many of the statistical relations used to estimate each component weight. Each iteration of the optimizer was started with the take-off weight from the previous set of independent design variables. An entire mission was simulated, including the reserve segment for each weight iteration. If the difference between the last estimate of gross take-off weight and the calculated weight was greater than 0.22 newton, another iteration was begun with an updated estimate. The program averaged about four weight iterations per performance function call for an entire optimization.

The aircraft was trimmed for cruising flight using a nonlinear, iterative method. The aerodynamic forces and moments were estimated using classical aeronautics and statistically normalized data for supercritical aerodynamics. The drag was estimated using references 17 and 21 to 23. The wing was assumed to be supercritical, and the pitching moment and drag were estimated as a function of wing thickness ratio, Reynolds number, Mach number, and sweep using the techniques from references 17 and 23 to 27.

Once the aircraft was trimmed, all the contributions of drag were summed to determine the required thrust and, hence, fuel consumption. A parabolic drag polar was assumed with a design $C_{L,o}$ of 0.4 representing the center of the airfoil section drag bucket. Drag contributions due to tail lift and tail/wing interference were estimated using biplane theory (refs. 2 and 28). The engine performance and weight were scaled from a baseline engine as suggested by reference 17. The engine operating characteristics were determined as a function of Mach number and altitude from a model developed in reference 18.

The modified direct operating cost MDOC used the summation of the following costs: depreciation, support, spares, delay, insurance, fuel, maintenance, landing fee, crew, attendants, fuel service, and control. The parameter MDOC differs from industry standard methods by the inclusion of support, delay, attendants, fuel-service, control, and landing-fee costs. Operating costs were estimated using the relationships found in references 29 to 32. This study was performed with the fuel cost set at 0.2 U.S. dollars per liter ($0.75 per gallon). Parallel studies were also completed with fuel costs of up to 0.4 U.S. dollars per liter ($1.50 per gallon). The depreciation costs were calculated using the airplane purchase price estimated from reference 17 and assuming a residual of 12 percent and a depreciation period of 14 years. The inclusion of active controls resulted in an appropriate increase in the purchase price and maintenance cost as indicated by references 4, 5, and 20. It was assumed that the same level of reliability and dispatchability could be maintained and, therefore, that the inclusion of this new technology would not result in increased delays or higher insurance rates.

After the performance function had been evaluated, the optimizer called a section of computer code which evaluated the set of constraints being applied. The list of available inequality constraints, which have upper and lower boundaries, is shown in table II. The constraints that were selected and the limits that were imposed were the means by which the design was specified. There were both operational or design constraints and flying-quality constraints.

A modified cost function was formed by adding penalty terms to the performance index function for each constraint function that violated its upper or lower limit. Each penalty was proportional to the square of the amount of the violation times a large weighting factor. When the optimizer minimized the modified cost function, it forced the constraint violations toward zero if the weighting factor was sufficiently large. Constraints that are on or near the boundary are said to be active.

Constraint functions that involved the aircraft operation during cruise utilized data saved in the data base during the cruise portions. The aircraft aerodynamic moments and forces were determined, and it was alternately trimmed out in take-off or landing configurations at the appropriate speeds to determine the performance, stability, and trim characteristics. The nondimensional stability derivatives used for these analyses were saved in the data base for approach and cruise configurations. These were converted to dimensional derivatives (ref. 33), and a fourth-order analysis of the longitudinal dynamics was performed using system routines at Langley Research Center. The roots of these differential equations were used to evaluate many of the flying-qualities parameters which were part of the constraint functions.

The optimization continued until satisfactory convergence was obtained. Typically, convergence required on the order of 1500 to 2200 calls of the performance function to generate an optimum augmented function, which resulted in the set of independent design variables with the minimum performance index that satisfied the selected constraint functions. This required about 1600 seconds of execution time using the Langley Research Center computer facilities.

Method of Comparison

The results were normalized using a baseline set of design specifications. These specifications were primarily the mission inputs of table I along with the military level I flying-qualities criteria for transport aircraft (ref. 34). Final values for both the independent and dependent design variables which resulted from the optimization of the baseline mission are shown in table III along with a number of performance indices. As mentioned previously, the modified direct operating cost per block hour was the figure-of-merit to which the configuration was optimized. Although the level I aircraft was obviously much more stable than current designs (static margin of nearly 43 percent), it represents a good baseline, since it used the most conservative of the proposed criteria for the unaugmented flying qualities of transports.

Since modified direct operating cost per block hour was the optimized performance index, all results are shown in terms of this quantity normalized by the baseline airplane performance. Specifically, percent savings in modified direct operating cost is the parameter that is plotted as a function of the various flying-qualities criteria being considered herein. It was calculated as follows:

$$P = \frac{\overline{\text{MDOC}} - \text{MDOC}}{\overline{\text{MDOC}}} \times 100$$

RESULTS AND DISCUSSION

Flying-Qualities Sensitivity Study

Static margin, or the degree of stick-fixed static stability, has been the parameter by which most analyses of stability augmentation systems for transports with active controls have been evaluated. Figure 3 shows the normalized modified-direct-operating-cost savings as a function of static margin during landing. The lower curve includes the impact of adding a flight control computer for augmenting the stability, while the upper curve represents not carrying an augmentation computer. The difference between the two curves is nearly constant since the computer is not scaled on the degree of instability; therefore, it represents an initial investment penalty for the development, certification, and maintenance of a required automatic flight control system. Although the inclusion of a large flight computer is expected to provide the capability for significant improvements in other areas such as safety, operating efficiency, and cost management, in this case it is charged entirely to the RSSAS system.

The savings in modified direct operating cost between an unaugmented stable aircraft representative of current configurations (20 percent static margin) and an augmented unstable aircraft (-10 percent static margin) is approximately 1.4 percent. Since fuel cost makes up about 40 percent of the modified direct operating cost per block hour, the fuel savings between these two airplanes is about 4.2 percent, as can be seen in table III. This compares favorably with the 3- to 5-percent savings previously estimated for this class of aircraft with similar reductions in static stability (refs. 1 and 2). In terms of 1979 dollars as compared with the unaugmented 20-percent static margin design case, this is equivalent to a savings of about $86,400 per year, or $1.21 million over the lifetime of the aircraft in MDOC. As fuel cost rises over the $0.20 per liter ($0.75 per gallon) used in this study, the savings projected will be even greater.

These savings include a best estimate of the incremental costs from the extra engineering, flight testing, and quality control requirements that yield the subsequent increase in purchase price. Additionally, the increase in maintenance costs is also reflected. The fact that such a large savings is still possible gives credence to the possibility that the technological and safety barriers that impede the use of RSSAS can be overcome in an economically feasible fashion.

The improvements noted in this comparison came principally from reductions in maximum take-off gross weight and in an improvement in maximum C_L/C_D. Schematic diagrams of the two aircraft are shown in figure 4, and key design data are compared in table III. The take-off gross weight was reduced 22 000 N (4946 lbf), with 7300 N (1641 lbf) of it attributable to the 32-percent reduction of the tail area. The 3.9-percent improvement in maximum C_L/C_D was due principally to a 17-percent reduction in total tail drag (wetted and induced).

Another parameter that is often considered during flying-qualities analyses is manuever margin, or the degree of maneuver stability (ref. 4). Maneuver stability is proportional to the elevator deflection required per unit gravity normal acceleration. Since it can be shown that the difference between static margin and maneuver margin is approximately constant for a given airplane (ref. 21), the fact that savings in modified direct operating cost have a similar trend for both static margin and maneuver margin is not surprising (figs. 3 and 5). Since pilots would be unable to control an aircraft with a negative maneuver margin, allowing negative maneuver margin as a design criterion for unaugmented flying qualities would be tantamount to assuming that the airplane would be lost in the event of a control system failure.

Time to double the amplitude of the longitudinal divergent dynamics is sometimes specified in flying-qualities criteria and considered in handling-qualities studies of unstable airplanes (ref. 7). Since time-to-double values result from unstable root locations of the dynamic equations, they are criteria appropriate for studying the unaugmented motions of the airplane. The savings in modified direct operating cost as a function of time to double amplitude in approach are shown in figure 6. Initially, as the time to double is reduced from a marginally unstable value of 55 seconds, small decreases in direct operating cost are obtained. However, as the time to double decreases further, the savings in direct operating cost increase rapidly until a value of 2 seconds for time to double amplitude. At this point, the data show that other constraints become critical and prevent any other improvements to be made in savings of modified direct operating cost from reducing the time-to-double constraint.

Flying-Qualities Design Criteria

Generally, when flying-qualities design criteria or regulations are developed, they encompass a variety of parameters in several flight conditions, for example, references 7 to 12 and 34. To provide the appropriate aerodynamic contribution to the stability, the unaugmented flying qualities must be specified. These inherent characteristics are significant when consideration is given to potential failure modes of the automatic flight control system. Philosophically, it becomes a compromise based on the minimum acceptable handling qualities.

One set of longitudinal-flying-qualities criteria that designers have applied to the design of transports configured with RSSAS is the military flying-qualities specifications (ref. 34). The short-period frequency requirement in approach is one of the active constraints if these military specifications are utilized as design criteria. Short-period frequency is plotted in figure 7 with the narrow range of applicability, in terms of n/α, for this study shown. Assuming constant n/α, the sensitivity of optimal direct operating cost to short-period frequency constraint is shown in figure 8.

As expected, substantial benefits were initially realized when relaxing the short-period frequency criterion from level I to levels II and III. The economic improvement was anticipated because it is generally accepted that level I for transports is extremely harsh (ref. 35). Observing the large tail surfaces of the baseline configuration (level I) in table III helps to illustrate this point. In fact, reference 35 points out that modern transports do not, in general, satisfy these criteria without augmentation, in spite of their generally acceptable flying qualities.

The problem with the military specifications and a number of other longitudinal-flying-qualities design criteria (refs. 10 and 11) is that they rely upon specifying modal damping ratios and frequencies. In the case of unstable airplanes, discussion of the dynamic longitudinal modes in terms of damping ratios and frequencies loses its meaning. Therefore, new longitudinal-flying-qualities design criteria are needed for transports configured with a reduced static margin.

The criteria proposed in references 8 and 9 have parameters which could be useful for imposing flying-qualities specifications for longitudinally unstable airplanes at the preliminary design level. These criteria are shown in figure 9. The abscissa and ordinate are coefficients of the characteristic polynomial that results from a linear analysis of the short-period mode, enabling easy consideration as constraint functions. However, the region indicated in the figure by a dashed line is where unaugmented transports designed with RSSAS are expected to fall, which is outside the area containing the flying-qualities data. This lack of appropriate data illustrates another problem in designing transports with RSSAS. Although the representation of flying qualities in figure 9 would be useful for developing longitudinal-flying-qualities design criteria, there is a need to collect simulator and flight test data with respect to the minimum acceptable handling qualities of transports.

Impact of Related Design Constants

Landing gear location.- Several design constants that were input for the baseline mission have a significant impact upon stability and control characteristics. One such factor is the main landing gear location. Current practice requires that its structure be located such that the loads are carried in the wing spar. Industry estimates that the maximum aft position that is structurally feasible is 65 percent of the mean aerodynamic chord (ref. 5). Since a margin between the center of gravity and landing gear is necessary to insure enough nose-wheel steering traction, and since the supercritical airfoil data used in OPDOT assume large pitching moments in cruise, the main gear position usually constrains the most aft allowable center-of-gravity position for transports with reduced static stability.

Figure 10 shows the impact of relaxing this constraint for each of the three levels of military flying qualities. Nearly 1 percent savings in modified direct operating cost per block hour could be realized by allowing the main gear to be located off the spar, provided that the structural weight penalties associated with the relocation would be negligible. Since this corresponds to a fuel savings of about 3 percent, it suggests a possible area for further research.

Loadability.- Another factor that had a bearing upon the results reported herein was an assumption that the allowable center-of-gravity range be at least 1.2 meters (4 feet). The impact of reducing the required loadability from 1.2 meters to 0.61 meter (2 feet) to 0 meters is shown in figure 11. It is readily apparent that the biggest improvements came from the first reduction to 0.61 meter. Only modest improvements were possible with further reduction, and this analysis ignores the cost of installing and operating a center-of-gravity control system that would certainly be necessary in this region of loadability. However, since the benefits in modified direct operating cost were slightly greater than 1 percent (3.2 percent savings in fuel), it may be worthwhile to pursue schemes to allow such reductions. The new generation of transport designs already incorporate load cells in the gear with computer monitoring for the optimal placement of cargo at the gate.

Take-off stabilizer trim angle.- Manufacturers have been expected to demonstrate that their transports are capable of satisfying the nose gear unstick requirement with the horizontal stabilizer in the most adverse trim position. This constraint, which is satisfied at the forward center-of-gravity limit, was shown to be extremely harsh. In fact, savings in direct operating cost of over 4 percent were indicated when the stabilizer was allowed to be trimmed to the position anticipated for climbout. It seems highly reasonable that for the corresponding $3.9 million that could be saved during the lifetime of the airplane, a suitable compromise between added complexity and safety could be reached to insure proper tail positioning during take-off.

Related Observations

Useful information for the aircraft designer would be a list of the design constraints that tended to be active at the optimal design point. It was determined from studying the program output that virtually without exception the following constraints were active at the converged solution point: (1) cruise thrust; (2) second-segment climb gradient; (3) landing field length; (4) nose-wheel steering traction; and (5) passenger volume. The first two were most sensitive to changes in thrust and wing aspect ratio, while landing field length was most influenced by wing area. Nose-wheel steering traction was a function of aft center of gravity, and passenger volume required a minimum fuselage length. As anticipated, the chosen flying-qualities constraint parameters were also active at the design point, and the solution was principally affected by this constraint through adjustments to the horizontal-tail area and aspect ratio.

Reference 36 predicts that the optimum tail load, in terms of drag, would be a download for high downwash gradients. The low-tail geometry of this study was located in regions of high downwash; therefore, it was no surprise when the optimum design points for all configurations had tail lift coefficients ranging between -0.05 and -0.12. This result was not assumed in the formulation, but a model of downwash and multiple-lifting-surface interference effects was included in the performance evaluation. The optimizer adjusted the design variables, principally in this case those which impacted tail volume and center of gravity, to obtain the minimum cost in the presence of control and stability constraints. This result helped to validate the conclusions of reference 36.

As indicated in references 12 and 13, an analysis was performed to insure that (1) the unaugmented configuration was capable of being augmented to good flying qualities; (2) the control deflections required for augmentation would be sufficiently small to avoid significant control surface drag contributions; and (3) the control surface deflection rates commanded by the automatic control system would be sufficiently low in turbulence to be achievable. These goals were accomplished by simulating a pitch-attitude-hold/pitch-rate-command autopilot in heavy turbulence.

The following factors were then available as inequality constraint functions in cruise and approach: (1) pitch attitude feedback gain, (2) pitch rate feedback gain, (3) variance of elevator deflection in turbulence, and (4) variance of elevator deflection rate in turbulence. However, except for when the unaugmented configuration was designed for extremely low time-to-double and maneuver margin, all configurations that the optimization generated satisfied these constraints. This was an indication that for the range of values considered in the research, the resulting configurations could be augmented to good flying qualities.

Since the price of fuel has already matched the $0.20 per liter ($0.75 per gallon) used in this study, a series of design runs was performed with higher fuel prices. When the baseline was reconfigured to reflect the inflated fuel prices, it was observed that the same trends existed with slightly greater magnitudes in savings with respect to the flying-qualities parameters. This indicates that the benefits of utilizing new active controls technologies to reduce the inherent static stability should be increasingly significant as fuel price escalates.

CONCLUDING REMARKS

A series of design runs utilizing a computer program for the optimal preliminary design of transport aircraft was used to study the impact of unaugmented flying-qualities design criteria and the influence of utilizing relaxed-static-stability augmentation systems. Transports optimally configured with relaxed static stability showed a potential savings in direct operating cost of 1.4 percent when compared with transports with conventional static margins. This translates into a fuel savings of 4.2 percent for the 5600-kilometer (3000-nautical-mile) range, 200-seat transport with a cruising Mach number of 0.8 which is considered in this report. Similar trends of savings can be observed when evaluating static margin, maneuver margin, or time to double amplitude as the constraining handling-qualities parameter.

It was observed that the same trends of savings in direct operating cost were expected for large variations in fuel price. It was also shown that efforts to remove the maximum rearward position constraint on the landing gear would be rewarded with gains of nearly 1 percent in modified direct operating cost. Additionally, a reduction of allowable center-of-gravity range from about 1.2 meters to about 0.6 meter could save nearly 1 percent in modified direct operating cost. A constraint to require the elevator to rotate the aircraft during take-off with the stabilizer in its most adverse position was found to be very harsh in terms of economic profitability, penalizing the aircraft over 4 percent in direct operating cost.

Constraints to insure enough thrust in cruise, to satisfy second-segment climb gradients, to fulfill landing field length requirements, to provide enough traction for nose wheel steering, and to allow enough volume for passengers were shown to be active at the design point along with the critical flying-qualities criteria. The optimum airplane tended to fly the cruise mission with a download on the tail as was predicted for an airplane with the horizontal tail in the influence of a strong downwash field.

In the course of the study, it was determined, through the hypothetical design and evaluation of a simple autopilot, that the designs considered were practically augmentable to good flying qualities. The rms deflections and rates of deflection of the elevator due to heavy turbulence were acceptable as were the feedback gains required to achieve satisfactory augmentation.

Most of the flying-qualities criteria proposed for unaugmented transports proved to be inappropriate, since trying to specify a modal frequency and damping ratio loses its significance for unstable airplanes. In particular, it was shown that the military specifications, when used for unaugmented airplane flying-qualities design criteria, were particularly harsh for this category of aircraft.

It is recommended that systematic flight and simulation research be undertaken to provide a data base for developing useful unaugmented flying-qualities design criteria for transports configured with relaxed static stability. Furthermore, an integrated effort between the designer and the handling-qualities specialist is required in order (1) to enhance the applicability of new criteria to design methodologies; (2) to maintain sufficient margins of flight safety; and (3) to insure that economic profitability is considered as any new criteria are developed.

Langley Research Center
National Aeronautics and Space Administration
Hampton, VA 23665
November 18, 1980

REFERENCES

1. Hood, Ray V.: Active Controls Changing the Rules of Structural Design. Astronaut. & Aeronaut., vol. 10, no. 8, Aug. 1972, pp. 50-55.

2. Mooij, H. A.: Handling Quality Criteria Development for Transport Aircraft With Fly-by-Wire Primary Flight Control Systems. Impact of Active Control Technology on Airplane Design, AGARD-CP-157, 1975, pp. 8-1 - 8-14.

3. Urie, D. M.; et al.: Accelerated Development and Flight Evaluation of Active Controls Concepts for Subsonic Transport Aircraft. Volume II - Aft C.G. Simulation and Analysis. NASA CR-159098, 1979.

4. Sizlo, T. R.; Berg, R. A.; and Gilles, D. L.: Development of a Low-Risk Augmentation System for an Energy-Efficient Transport Having Relaxed Static Stability. NASA CR-159166, 1979.

5. Boeing Commercial Airplane Co.: Integrated Application of Active Controls (IAAC) Technology to an Advanced Subsonic Transport Project - Initial ACT Configuration Design Study, Final Report. NASA CR-159249, 1980.

6. Mooij, H. A.: Handling Quality Criteria Development for Transport Aircraft With Fly-by-Wire Primary Flight Control Systems. NLR TR 74141 U, Nat. Aerosp. Lab. (Amsterdam), May 1977.

7. Grantham, William D.; and Deal, Perry L.: Simulator Study of Minimum Acceptable Level of Longitudinal Stability for a Representative STOL Configuration During Landing Approach. NASA TN D-7733, 1974.

8. Harper, Robert P., Jr.: Flight Evaluations of Various Longitudinal Handling Qualities in a Variable-Stability Jet Fighter. WADC Tech. Rep. 55-299, U.S. Air Force, July 1955.

9. Chalk, Charles R.: Additional Flight Evaluations of Various Longitudinal Handling Qualities in a Variable-Stability Jet Fighter. WADC Tech. Rep. 57-719, Pts. I & II, U.S. Air Force, 1958. (Available from DTIC as AD 142 184 and AD 206 071.)

10. Design Objectives for Flying Qualities of Civil Transport Aircraft. ARP 842, Soc. Automot. Engrs., Aug. 1, 1964.

11. Chalk, Charles R.; DiFranco, Dante A.; Lebacqz, J. Victor; and Neal, T. Peter: Revisions to MIL-F-8785B (ASG) Proposed by Cornell Aeronautical Laboratory Under Contract F33615-71-C-1254. AFFDL-TR-72-41, U.S. Air Force, Apr. 1973.

12. Sliwa, Steven M.: Impact of Longitudinal Flying Qualities Upon the Design of a Transport With Active Controls. AIAA-80-1570, Aug. 1980.

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

14. Olsson, D. M.: A Sequential Simplex Program for Solving Minimization Problems. Qual. Technol., vol. 6, no. 1, Jan. 1974, pp. 53-57.

15. Olsson, Donald M.; and Nelson, Lloyd S.: The Nelder-Mead Simplex Procedure for Function Minimization. Technometrics, vol. 17, no. 1, Feb. 1975, pp. 45-51.

16. Park, Stephen K.: A Transformation Method for Constrained-Function Minimization. NASA TN D-7983, 1975.

17. Nicolai, Leland M: Fundamentals of Aircraft Design. School of Eng., Univ. of Dayton, Dayton, Ohio, c.1975.

18. Aggarwal, R.; et al.: An Analysis of Fuel Conserving Operational Procedures and Design Modifications for Bomber/Transport Aircraft. AFFDL-TR-78-96, Volume II, U.S. Air Force, July 1978. (Available from DTIC as AD A062 609.)

19. Oman, B. H.: Vehicle Design Evaluation Program. NASA CR-145070, 1977.

20. Anderson, R. D.; Flora, C. C.; Nelson, R. M.; Raymond, E. T.; and Vincent, J. H.: Development of Weight and Cost Estimates for Lifting Surfaces With Active Controls. NASA CR-144937, 1976.

21. Perkins, Courtland D.; and Hage, Robert E.: Airplane Performance Stability and Control. John Wiley & Sons, Inc., c.1949.

22. Hoerner, Sighard F.: Fluid-Dynamic Drag. Hoerner Fluid Dynamics (Brick Town, N. J.), c.1965.

23. Kyser, Albert C.: An Elementary Analysis of the Effect of Sweep, Mach Number, and Lift Coefficient on Wing-Structure Weight. NASA TM-74072, 1977.

24. Harris, Charles D.: Aerodynamic Characteristics of a 14-Percent-Thick NASA Supercritical Airfoil Designed for a Normal-Force Coefficient of 0.7. NASA TM X-72712, 1975.

25. Bartlett, Dennis W.: Wind-Tunnel Investigation of Several High Aspect-Ratio Supercritical Wing Configurations on a Wide-Body-Type Fuselage. NASA TM X-71996, 1977.

26. USAF Stability and Control Datcom. Contracts AF33(616)-6460 and F33615-76-C-3061, McDonnell Douglas Corp., Oct. 1960. (Revised Apr. 1978.)

27. Roskam, Jan: Methods for Estimating Stability and Control Derivatives of Conventional Subsonic Airplanes. Pub. by the author (Dep. Aerosp. Eng., Univ. of Kansas, Lawrence, Kansas), c.1973.

28. McLaughlin, Milton D.: Calculations, and Comparison With an Ideal Minimum, of Trimmed Drag for Conventional and Canard Configurations Having Various Levels of Static Stability. NASA TN D-8391, 1977.

29. American Airlines: A New Method for Estimating Current and Future Transport Aircraft Operating Economics. NASA CR-145190 (Rev.), 1978.

30. Maddalon, Dal V.: Estimating Airline Operating Costs. NASA TM-78694, 1978.

31. Economic Impact of Applying Advanced Engine and Airframe Technologies to Transport Aircraft. NASA CR-132268, 1973.

32. Assessment of the Application of Advanced Technologies to Subsonic CTOL Transport Aircraft. NASA CR-112242, 1973.

33. McRuer, Duane; Ashkenas, Irving; and Graham, Dunstan: Aircraft Dynamics and Automatic Control. Princeton Univ. Press, 1973.

34. Chalk, C. R.; Neal, T. P.; Harris, T. M.; Pritchard, F. E.; and Woodcock, R. J.: Background Information and User Guide for MIL-F-8785B(ASG), "Military Specification - Flying Qualities of Piloted Airplanes." AFFDL-TR-69-72, U.S. Air Force, Aug. 1969. (Available from DTIC as AD 860 856.)

35. Barnes, A. G.: Handling Qualities Specification Deficiencies. AGARD-AR-89, 1975.

36. Sachs, Gottfried: Minimum Trimmed Drag and Optimum c.g. Position. J. Aircr., vol. 145, no. 8, Aug. 1978, pp. 456-459.

TABLE I.- KEY DESIGN CONSTANTS UTILIZED FOR DESIGN OPTIMIZATION

(a) Mission

Cruise Mach number	0.80
Divergence Mach number	0.84
Design range, km	5600
Number of seats	200
Cargo, N	33 400
Maximum lift coefficient	3.15
Landing field requirement, m	2440
Take-off field requirement, m	3050

(b) Geometry

Wing sweep angle, deg	26.4
Wing thickness ratio	0.12
Wing taper ratio	0.38
Wing incidence angle, deg	2
Wing geometric twist, deg	5
Tail thickness ratio	0.10
Tail sweep angle, deg	30
Tail taper ratio	0.4
Vertical-tail sweep, deg	35
Ratio of rudder area to vertical-tail area	0.30
Ratio of elevator chord to horizontal-tail chord	0.25
Ratio of flap span to wing span	0.6
Maximum flap deflection, deg	45
Fuselage diameter, m	5.08
Height of aerodynamic center above c.g., fraction MAC	0.08
Height of thrust vector above c.g., fraction MAC	-0.12
Height of horizontal tail above c.g.	0
Number of engines	2

TABLE I.- CONCLUDED

(c) Economics

Fuel cost, $/L	0.20
Load factor	0.55
Passenger revenue, ¢/seat-km	4.9
Utilization rate, hr/yr	3200
Depreciation period, yr	14
Residual value, %	12
Tax rate	0.48
Year of study	1979
Assumed annual inflation rate	0.07
Number of prototype aircraft	2
Aircraft fleet size	250
Initial production rate, per month	0.5
Full production rate, per month	5
Engineering rate (1974), $/hr	19.55
Tooling rate (1974), $/hr	14.00
Labor rate (1974), $/hr	10.90
Engines for test aircraft	3
Ratio of manufacturer's airframe weight to take-off weight	0.75

(d) Miscellaneous

Maximum dynamic pressure, N/m^2	5.13
Pressurized volume, m^3	178.2
Number of pilots	3
Number of attendants	8
Air conditioning flow rate, kg/min	200
Autopilot channels (with multiplexers)	5
Generator capacity, kV-A	750
Maintenance complexity factor	1.6
Hydraulics volume flow rate, L/min	300
Number of inertial platform systems	1
Ratio of auxiliary-power-unit on-time to engine on-time	0.1
Ratio of first class to economy seating	0.15
Maximum speed, m/s	248.5
Airfoil design lift coefficient	0.5
Baseline engine	CF-6
Elevator servo time constant, sec	0.1
Curved windshield	
Supercritical airfoil technology	
Some nonlinear aerodynamics terms	

TABLE II.- SAMPLE INEQUALITY CONSTRAINT FUNCTIONS AVAILABLE DURING DESIGN OPTIMIZATION

- Mission
  - Cruise thrust
  - Second-segment climb gradient
  - Missed-approach climb gradient
  - Landing field length
  - Take-off field length
  - Passenger volume
  - Cruise altitude
  - Fuel volume
  - Cruise lift coefficient

- Control
  - Nose gear steering traction
  - Nose gear unstick during take-off
  - Tail-lift-coefficient stall margin in approach
  - Elevator deflection[a]

- Stability
  - Static margin[a]
  - Maneuver margin[a]
  - Short period frequency[a]
  - Short period damping[a]
  - Phugoid frequency[a]
  - Phugoid damping[a]
  - Mode frequency ratio[a]
  - Time-to-half (double)[a]
  - Vertical response factor[a]

- Autopilot
  - Pitch feedback gain[a]
  - Pitch rate feedback gain[a]
  - Elevator variance[a]
  - Elevator rate variance[a]

[a] Available for both cruise and approach configurations.

TABLE III.- CHARACTERISTICS OF SAMPLE

Design case	Independent design variables							Some					
	S_w, m^2	AR_w	ℓ_f, m	S_t, m^2	AR_t	T, kN	c.g., % MAC	Wt_w, kN	Wt_t, kN	Wt_e, kN	Wt_{to}, kN	Fuel, L	$C_{D,o,w}$
Level I[a] (baseline)	199.3	10.75	52.7	103.6	6.38	338.4	36	145.5	44.2	677.7	1230	26 033	0.0078
Level II[a]	188.7	11.66	↓	84.4	5.16	313.2	46	149.4	34.4	657.0	1192	24 235	.0079
Level III[a]	188.6	11.65	↓	84.1	5.15	313.2	46	149.1	34.3	656.4	1191	24 223	.0079
Static margin = -20%	184.1	12.55	↓	43.0	5.34	292.6	47	154.8	24.5	640.0	1155	22 501	.0080
Static margin = -10%	183.6	12.46	↓	49.7	5.16	294.7	↓	153.9	25.9	641.7	1159	22 569	↓
Static margin = -5%	184.6	12.45	↓	51.8	5.71	295.8	↓	153.9	28.1	646.9	1167	22 709	↓
Static margin = 0%	185.9	12.50	↓	53.9	6.41	297.1	↓	157.1	30.8	654.0	1175	22 970	↓
Static margin = 5%	186.3	12.28	↓	58.2	6.33	300.2	↓	154.8	31.8	654.1	1177	23 197	↓
Static margin = 10%	185.5	12.10	↓	66.4	5.06	302.5	↓	151.2	29.8	647.9	1173	23 402	↓
Static margin = 20%	187.4	11.90	↓	73.4	5.61	307.6	↓	↓	33.5	655.2	1185	23 807	.0079
Static margin = 20%[b]	186.8	11.94	↓	73.3	5.55	306.7	↓	↓	33.2	652.3	1181	23 716	.0080
Maneuver margin = 0%	184.3	12.37	↓	54.5	5.11	298.1	↓	153.7	27.0	644.6	1164	22 907	↓
Maneuver margin = 10%	185.4	12.20	↓	60.4	5.54	300.2	↓	152.8	29.9	648.6	1172	23 198	↓
Time to double = 55 sec	184.5	12.19	↓	59.1	4.63	299.3	↓	151.4	26.6	641.9	1163	23 077	↓
Time to double = 40 sec	184.0	12.10	↓	59.1	4.61	299.7	↓	150.4	26.6	640.6	1162	23 080	↓
Time to double = 20 sec	183.7	↓	↓	56.8	4.88	299.9	↓	149.8	26.9	640.1	1161	23 027	↓
Time to double = 3 sec	181.6	↓	↓	43.8	4.95	296.8	↓	147.3	23.6	630.2	1146	22 599	↓

[a] Military level specifications from MIL-F-8785B (ref. 34).
[b] No active control systems included in cost or weight estimates.

CONFIGURATIONS GENERATED DURING STUDY

dependent design variables								Performance indices			
$C_{D,o,t}$	$C_{D,o,tot}$	$C_{L,t}$	$C_{D,t}$	$(L/D)_{max}$	$C_{A\$}$, millions of \$	$C_{F\$}$, \$/block hr	$C_{M\$}$, \$/block hr	MDOC \$/block hr	IOC, \$/block hr	ROI, %	FARE, \$/seat-km
0.0037	0.0193	-0.124	0.0045	19.1	15.87	736	163	1978	904	12.9	0.051
.0032	.0190	-.112	.0039	20.1	15.36	685	150	1904	900	14.1	.050
.0032	.0190	-.112	.0039	20.1	15.35	685	160	1904	900	14.1	.050
.0018	.0177	-.206	.0028	21.4	14.94	635	157	1836	897	15.2	.049
.0020	.0179	-.179	.0030	21.2	14.98	642	↓	1844	898	15.0	↓
.0021	.0180	-.173	↓	21.2	15.06	645		1851	↓	14.9	
.0022	.0181	-.166		21.2	15.16	649	158	1859		14.7	
.0024	.0182	-.154	.0031	21.0	15.19	655	158	1867	899	14.6	
.0026	.0185	-.135	.0034	20.6	15.14	661	159	1870	899	14.6	
.0029	.0187	-.123	.0036	20.4	15.28	673	159	1888	900	14.3	.050
.0029	.0187	-.123	.0036	20.4	14.96	670	155	1871	896	14.8	.049
0022	.0181	-.164	.0031	21.0	15.05	647	158	1853	898	14.9	↓
.0024	.0182	-.149	.0033	20.8	15.13	656	↓	1860	899	14.7	
.0023	↓	-.151	↓	20.8	15.03	652		1856	↓	14.9	
↓		-.150		↓	15.02	652		1856		↓	
	.0181	-.156	.0032		15.02	651	157	1855			
.0018	.0177	-.199	.0029	20.9	14.86	639	155	1836	898	15.3	.048

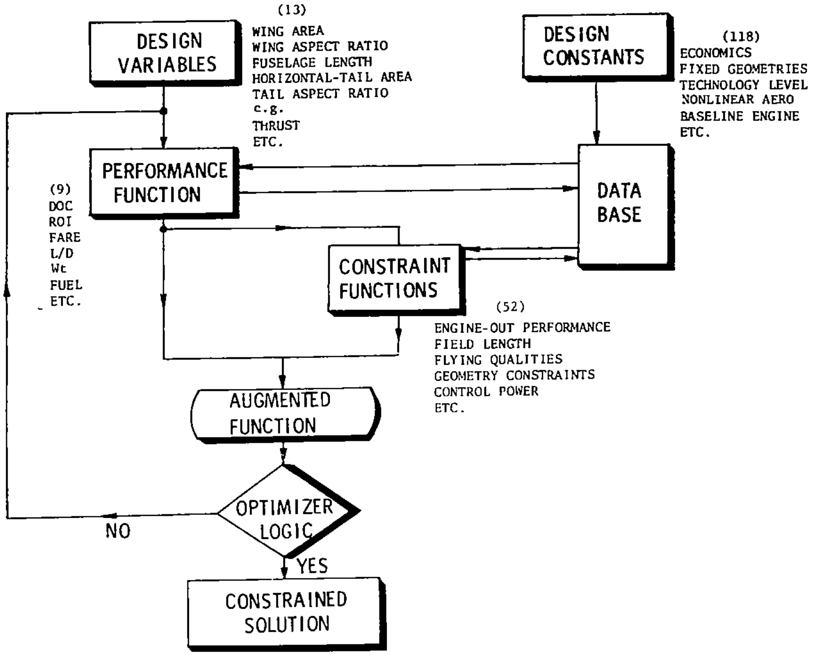

Figure 1.- Schematic diagram representing the constrained parameter optimization logic. Numbers in parentheses are number of parameters available in OPDOT (ref. 13).

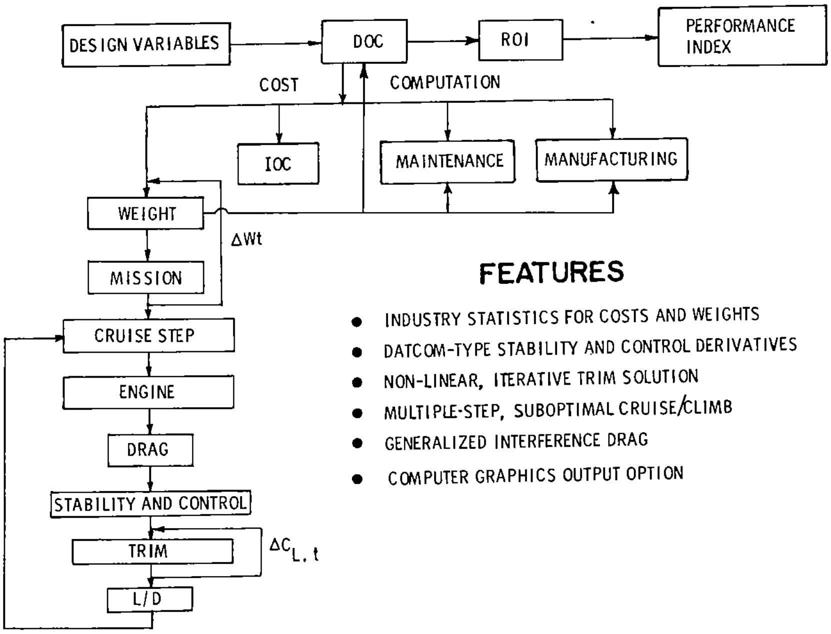

Figure 2.- Hierarchy of logic flow for evaluating the performance indices.

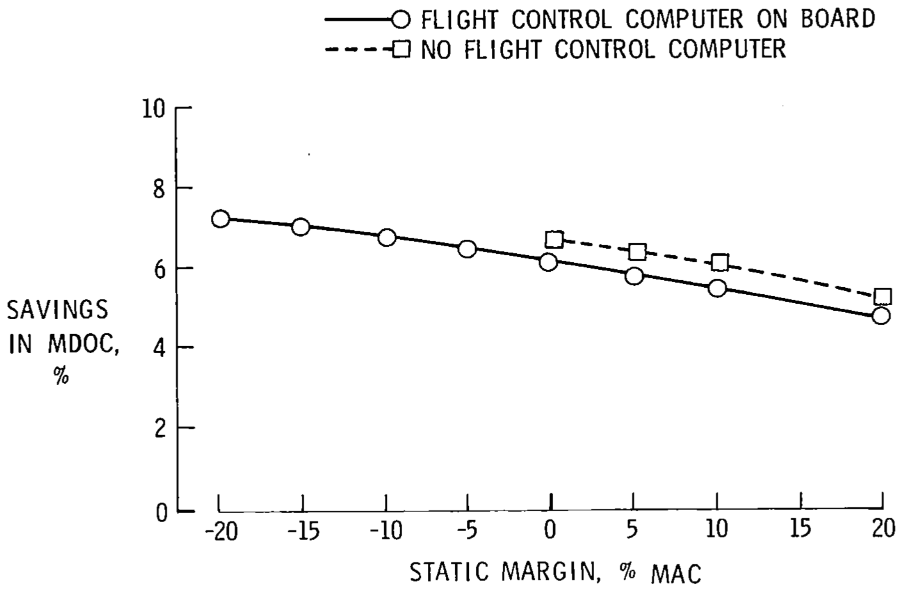

Figure 3.- Percent savings in modified direct operating cost with respect to the baseline configuration as a function of static margin required during landing.

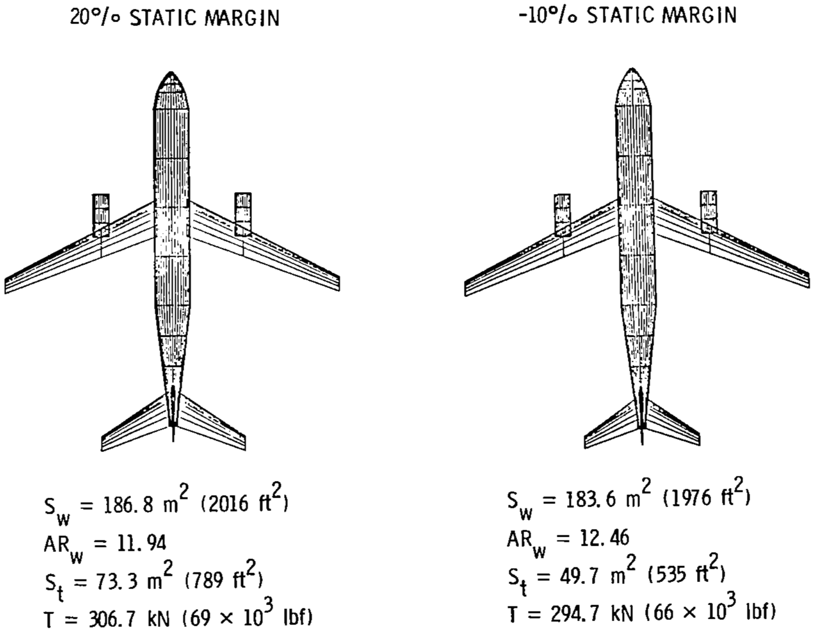

Figure 4.- Sketches of two optimally designed airplanes. The left airplane is representative of a transport sized with conventional flying qualities, and right transport was sized with relaxed static stability and requires an RSSAS system for adequate flying qualities.

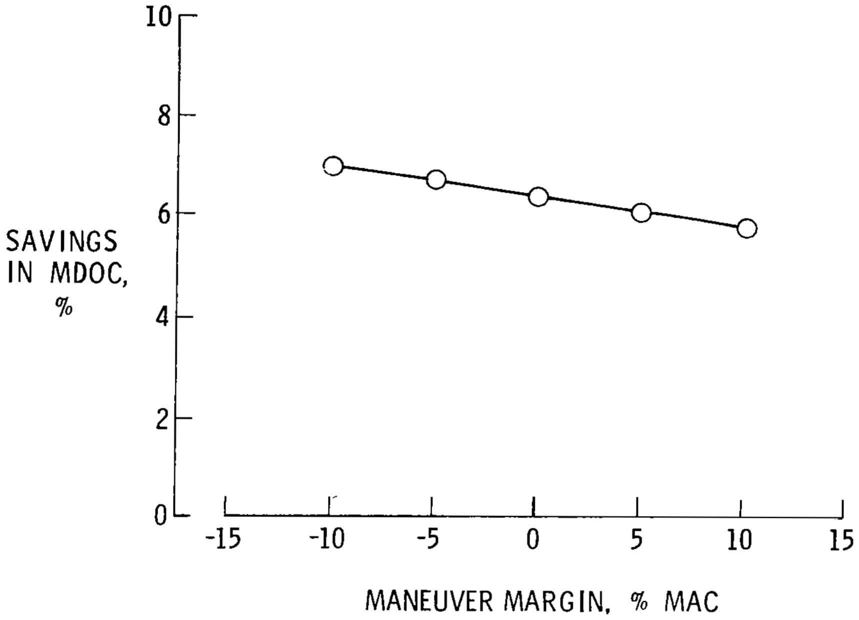

Figure 5.- Percent savings in modified direct operating cost with respect to the baseline configuration as a function of minimum maneuver margin required in approach. It should be noted that unaugmented aircraft with negative maneuver margins would be uncontrollable.

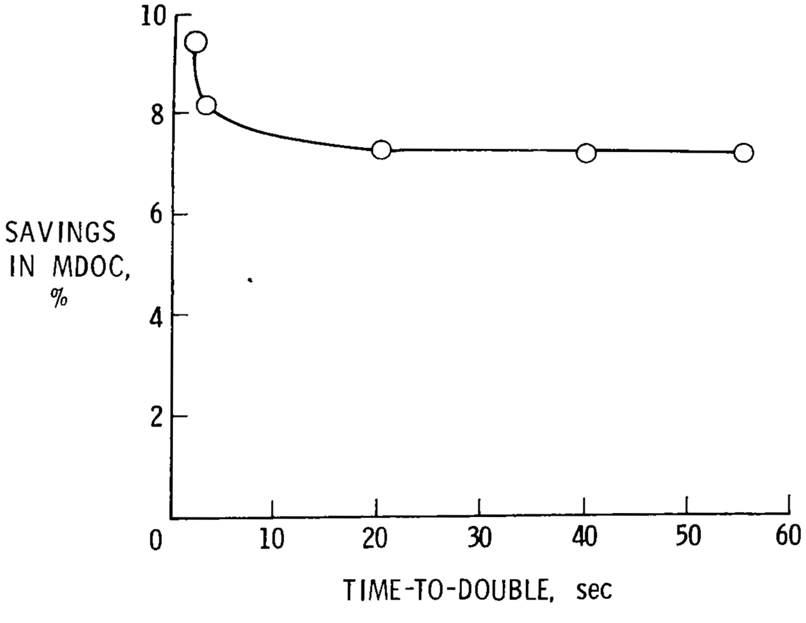

Figure 6.- Percent savings in modified direct operating cost with respect to the baseline configuration as a function of minimum time to double amplitude in approach.

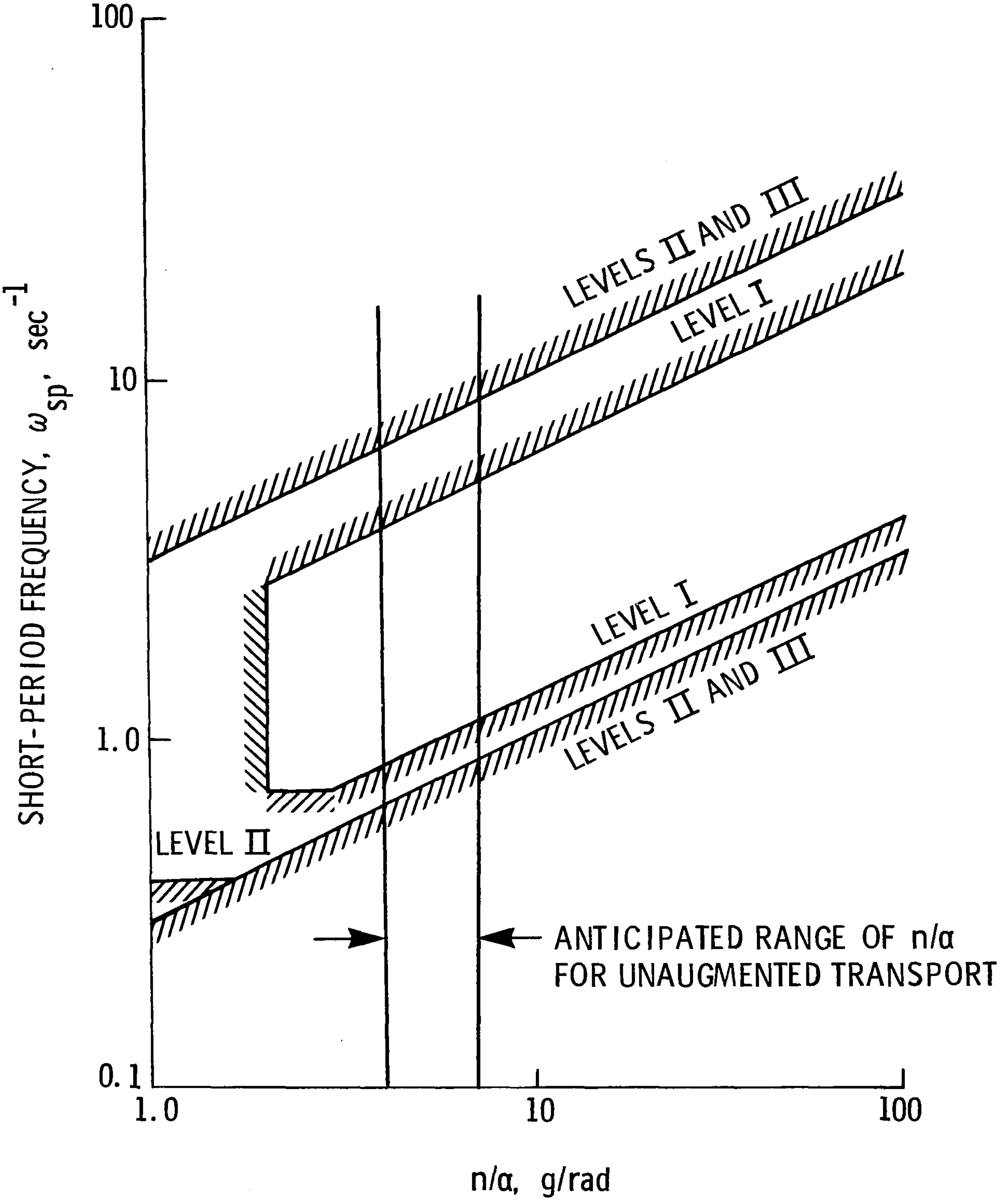

Figure 7.- Short-period frequency boundaries for military specifications (ref. 34).

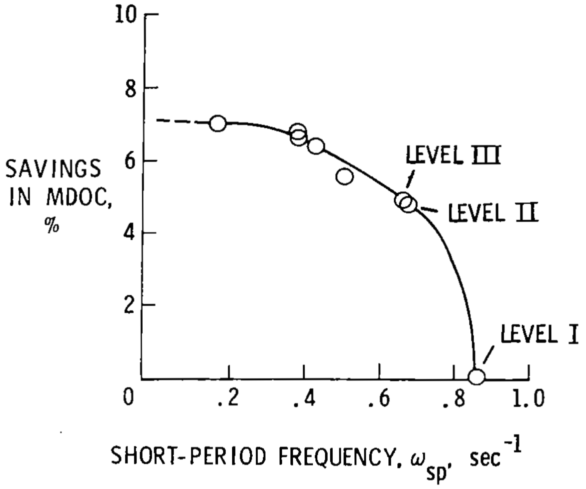

Figure 8.- Sensitivity of percent savings in modified direct operating cost with respect to baseline configurations to short-period-frequency constraint.

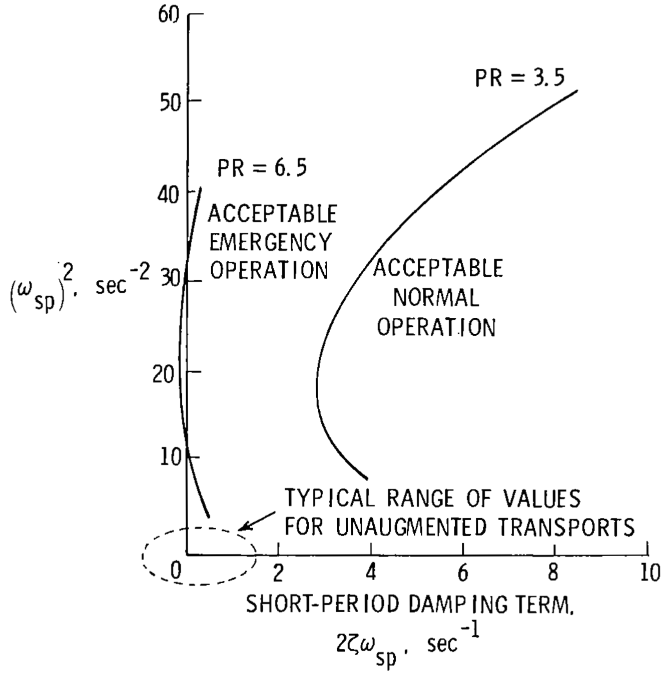

Figure 9.- Proposed boundaries of longitudinal short-period characteristics for specifying flying qualities from reference 8.

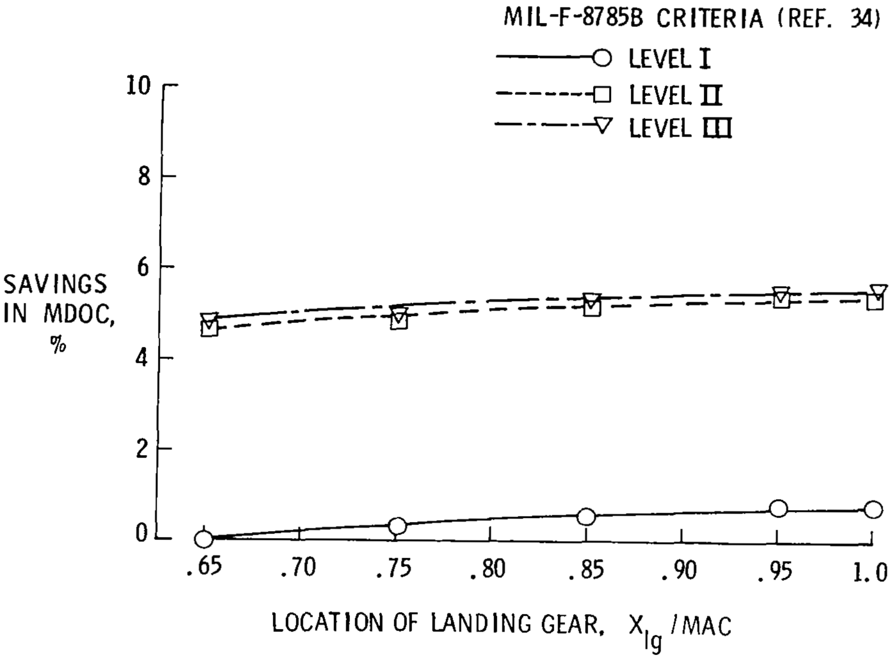

Figure 10.- Impact of maximum aft location of landing gear upon percent savings in modified direct operating cost with respect to baseline configuration.

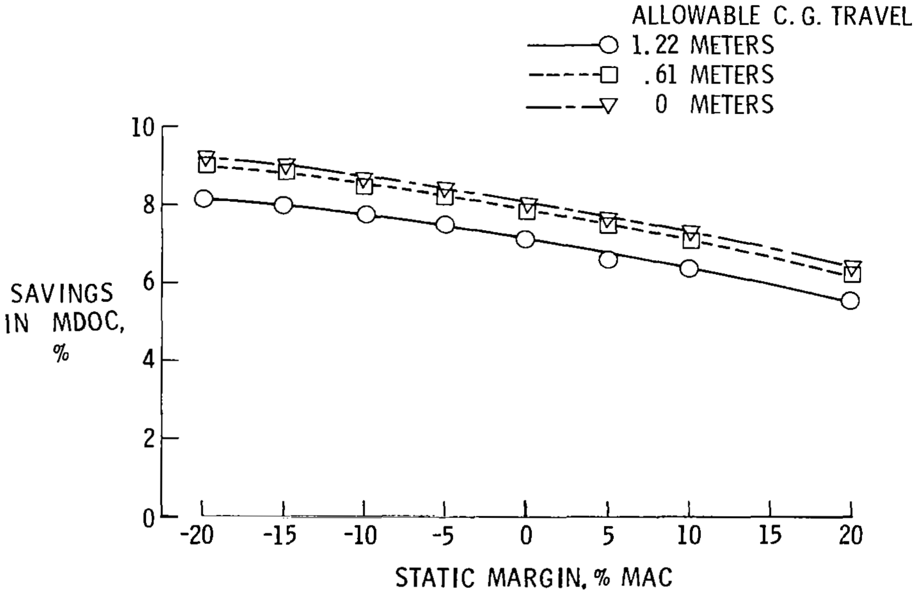

Figure 11.- Sensitivity of percent savings in modified direct operating cost with respect to baseline configuration to allowable center-of-gravity travel as a function of required static margin in approach.

1. Report No. NASA TP-1760	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle ECONOMIC EVALUATION OF FLYING-QUALITIES DESIGN CRITERIA FOR A TRANSPORT CONFIGURED WITH RELAXED STATIC STABILITY		5. Report Date December 1980 6. Performing Organization Code 505-34-33-05
7. Author(s) Steven M. Sliwa		8. Performing Organization Report No. L-13944
9. Performing Organization Name and Address NASA Langley Research Center Hampton, VA 23665		10. Work Unit No. 11. Contract or Grant No.
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, DC 20546		13. Type of Report and Period Covered Technical Paper 14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract

Direct constrained parameter optimization was used to optimally size a medium-range transport for minimum direct operating cost. Several stability and control constraints were varied to study the sensitivity of the configuration to specifying the unaugmented flying qualities of transports designed to take maximum advantage of relaxed-static-stability augmentation systems. Additionally, a number of handling-qualities-related design constants were studied with respect to their impact on the design.

17. Key Words (Suggested by Author(s)) Conceptual design of aircraft Constrained optimization Nonlinear programming Economics Flying qualities Relaxed static stability Stability augmentation systems	18. Distribution Statement Unclassified - Unlimited Subject Category 08

19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 27	22. Price A02

For sale by the National Technical Information Service, Springfield, Virginia 22161

National Aeronautics and
Space Administration

Washington, D.C.
20546

Official Business
Penalty for Private Use, $300

THIRD-CLASS BULK RATE

Postage and Fees Paid
National Aeronautics and
Space Administration
NASA-451

U.S.MAIL

10 1 1U,A, 121280 S00903DS
DEPT OF THE AIR FORCE
AF WEAPONS LABORATORY
ATTN: TECHNICAL LIBRARY (SUL)
KIRTLAND AFB NM 87117

NASA

POSTMASTER: If Undeliverable (Section 158
Postal Manual) Do Not Return