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A SAFETY MARGIN AND FLIGHT REFERENCE SYSTEM AND DISPLAY FOR POWERED-LIFT AIRCRAFT*

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SUMMARY

A study was conducted to explore the feasibility of a safety margin and flight reference system for those powered-lift aircraft which require a backside piloting technique. The main objective was to display multiple safety margin criteria as a single variable which could be tracked both manually and automatically and which could be monitored in order to derive safety margin status. The study involved a pilot-in-the-loop analysis of several system concepts and a simulator experiment to evaluate those concepts showing promise. A system was ultimately configured which yielded reasonable compromises in controllability, status information content, and the ability to regulate safety margins at some expense of the allowable low speed flight path envelope. It was necessary, however, to utilize an integrated display of two variables — one to be tracked in a compensatory manner and one to be monitored. The variables themselves consisted of linear combinations of the computed critical safety margin and pitch attitude, and the proportions of the combinations were definable in terms of the aforementioned compromises.

SYMBOLS

k	Weighting coefficient for pitch attitude
N_H	Engine rpm
V	Airspeed
V_{min}	Minimum airspeed at approach thrust
V_{min_m}	Minimum airspeed at maximum thrust
α	Angle of attack
α_{max}	Maximum allowable angle of attack
γ	Aerodynamic flight path angle
θ	Pitch attitude

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INTRODUCTION

The pilot's control technique for a powered-lift aircraft in the approach flight phase is inherently different from that for a conventional aircraft. The pilot (or autopilot) of the powered-lift aircraft cannot simply use 1.3 times the power-off stalling speed (for the approach configuration) as the target airspeed or "flight reference" and be guaranteed adequate safety margins. Since a powered-lift aircraft derives a significant part of its lift from a thrust vector which is inclined nearly perpendicular to the flight path, the minimum speed is determined to a large extent by the thrust or power setting. This is in dramatic contrast to the characteristics of a conventional aircraft as shown in Fig. 1. Note that the approach speed for a powered-lift aircraft may be in the neighborhood of the idle thrust stalling speed (Point A in Fig. 1).

In addition to the problem of selecting a suitable speed (or other parameter) to use as a flight reference which will ensure adequate safety margins, the pilot may have to cope with some other unusual flight characteristics. For example, most powered-lift aircraft approach at speeds on the "backside" of the thrust required curve. Consequently, a "backside" or "STOL" control technique is usually used, i.e., the pilot uses pitch attitude to regulate airspeed and modulates thrust to control flight path. A typical flight characteristic resulting from this mode of control and from the thrust vector being inclined nearly perpendicular to the flight path is shown in Fig. 2. That is, if the pilot is using airspeed as a flight reference (i.e., maintaining a constant airspeed), it can be seen that to steepen the descent path angle the pilot must increase pitch attitude! This is contradictory to all normal practice and can make airspeed a very confusing flight reference.

Because of these problems, the pilots of airplanes such as the NASA Augmentor Wing Jet STOL Research Aircraft (AWJSRA) must use a combination of airspeed, angle of attack, and pitch attitude as a flight reference. Only through extensive experience are these pilots able consistently to maintain adequate safety margins. While this use of a complex flight reference has been acceptable in the research environment, it would not be acceptable operationally.

OBJECTIVE

The objective of the program, therefore, was to find a single display to be used for maintaining a safe flight condition in powered-lift aircraft. Several features needed to be considered, however, which significantly complicated the design of such a system. These are shown in Fig. 3.

The present study was primarily a feasibility study and was limited to an analysis and simulation phase. The results to be presented were obtained in the context of (i) an existing powered-lift STOL airplane (NASA AWJSRA),

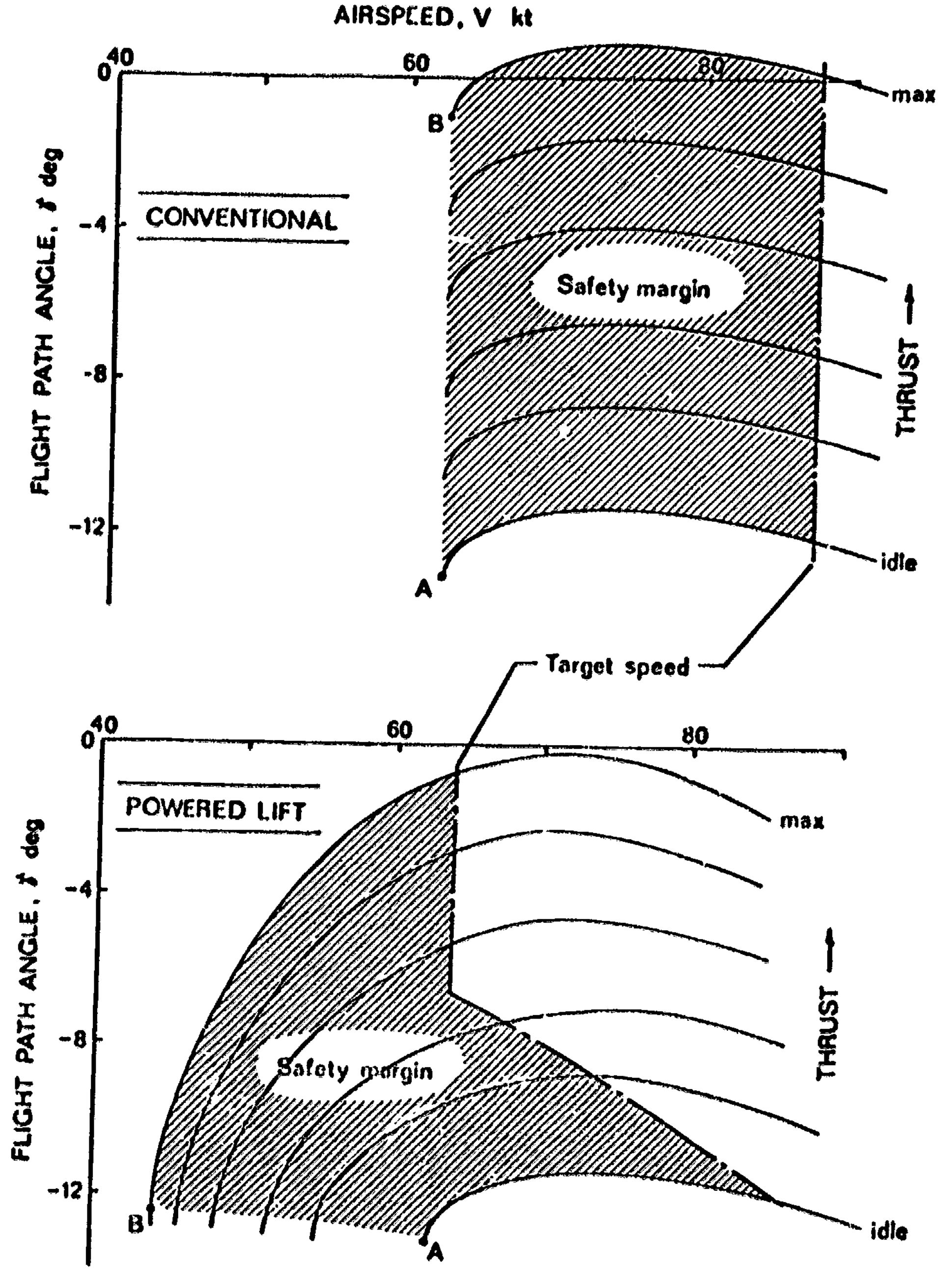

Figure 1. Comparison of γ - V Plots Between a Conventional and a Powered-Lift Aircraft.

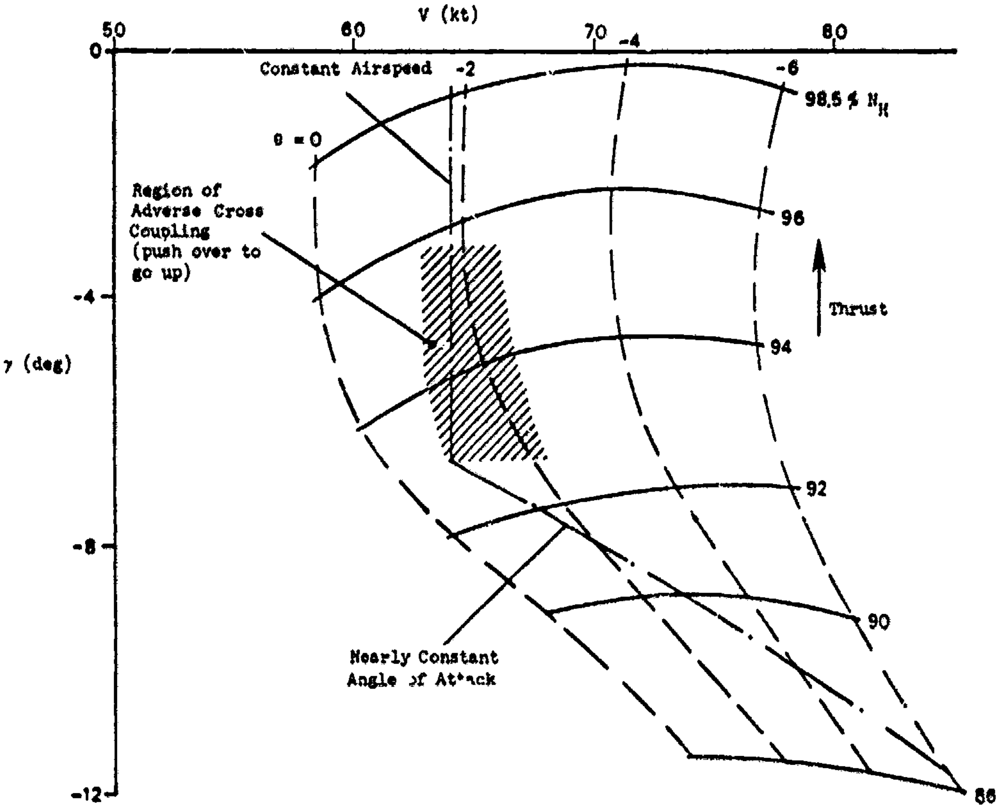

Figure 2. γ - V Curve Showing Region of Adverse Cross Coupling Along Trajectory of Desired Airspeed.

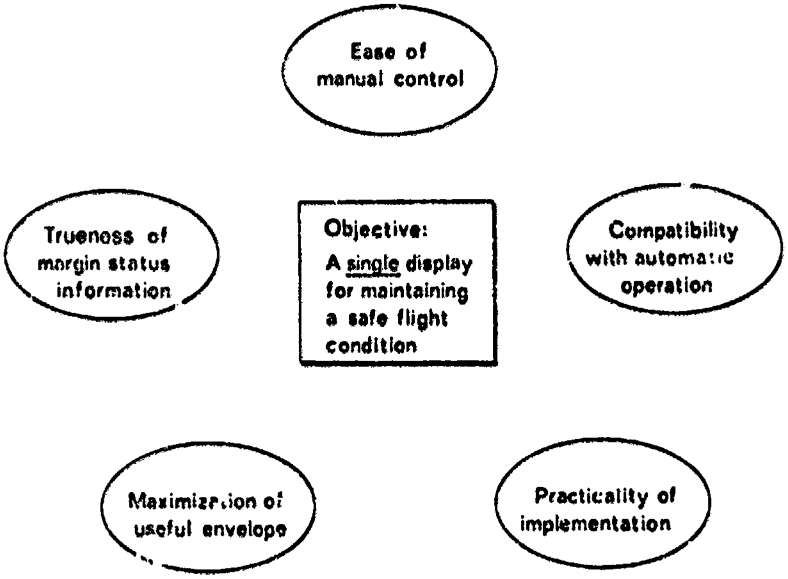

Figure 3. Tradeoffs Involved in the System Design.

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(ii) existing avionics hardware (STOLAND guidance, control, and navigation system, Ref. 1), and (iii) severe atmospheric disturbances encountered during the landing approach flight phase.

TECHNICAL APPROACH

An extensive study of airworthiness requirements which is described in Refs. 2 and 3, defined the required safety margin criteria for powered-lift aircraft in terms of the instantaneous angle of attack and airspeed. The suggested criteria from Ref. 2 are listed in Table 1. Figure 4 shows these criteria superimposed on the AWJSRA flight envelope. The present study assumed these safety margin criteria for the purpose of defining the available flight envelope. Note that only two criteria dominate, i.e., airspeed must be greater than the minimum speed at maximum thrust plus 20 knots and the angle of attack must be such that a 20 knot vertical gust will not result in exceeding the maximum allowable angle of attack. The resulting flight envelope is bounded in Fig. 4 by the lines labeled "minimum safe airspeed."

Table 1. Safety Margin Criteria.

(All Engines Operating)

$$V > 1.15\, V_{min} \text{ (approach thrust)}$$

$$V > V_{min} + 10 \text{ knots (approach thrust)}$$

$$V > 1.3\, V_{min_m} \text{ (maximum thrust)}$$

$$\left.\begin{array}{l} V > V_{min_m} + 20 \text{ knots (maximum thrust)} \\ \alpha < \alpha_{max} - \sin^{-1} \dfrac{20 \text{ knots}}{V} \text{ (vertical gust margin)} \end{array}\right\} \text{Most Critical Criteria}$$

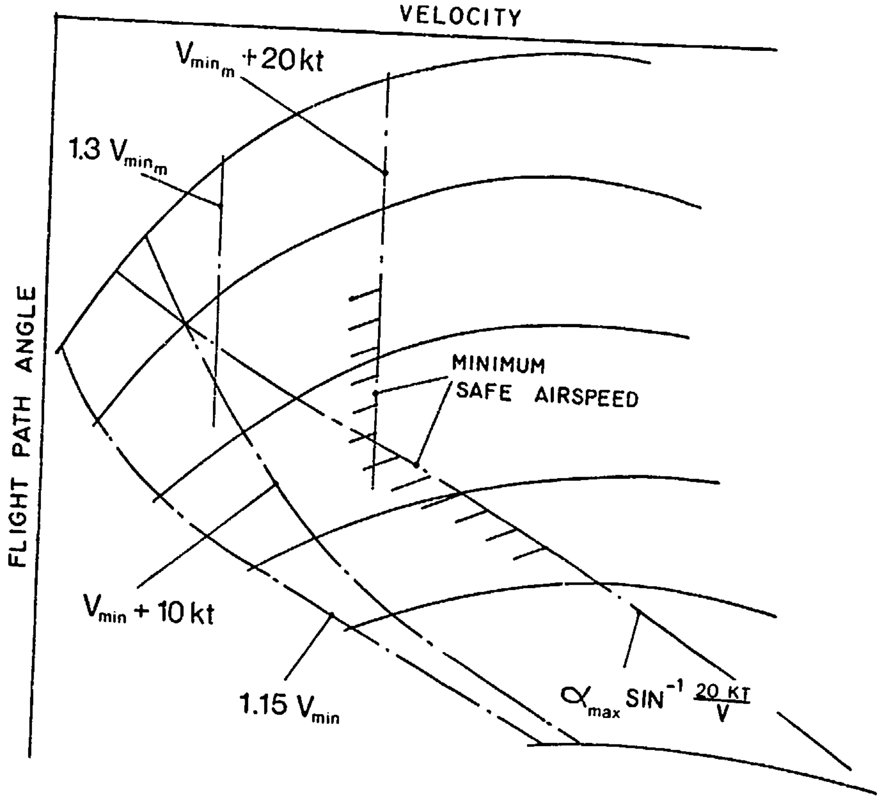

Figure 4. Relationship of Various Safety Margin Criteria. (Corresponding to Table 1 for the AWJSRA)

A large number of possible flight reference and safety margin mechanizations that were consistent with this flight envelope were examined and are described in detail in Ref. 4. The analysis utilized multiloop control system analysis methods and considered: (1) ease of control, (2) display of safety margin status, (3) pilot and automatic system performance in maintaining safety margins, and (4) system mechanization as they relate to sensor and computational requirements. The purpose of the analysis was to sort through the large number of possibilities to find a few which would be worthwhile examining during the simulation phase.

RESULTS

From the large number of implementation concepts considered, one was found to meet design objectives satisfactorily. Although it consisted of a single display, two variables were involved. One variable was actively tracked and thus served as a flight reference. The other variable was simply monitored in order to obtain high quality status information. This implementation can be summarized as:

[Tracked Variable] = [Actual Margin] + k · [Pitch Attitude]

[Monitored Variable] = [Actual Margin]

where the actual margin is taken as the most critical of applicable airspeed and angle of attack safety margin criteria from Table 1.

It is significant that the tracked variable was composed of a simple linear combination of actual margin and pitch attitude. This implementation permitted a direct tradeoff between ideal status information and easy controllability depending upon the weighting factor, k. A single value of k was found to provide satisfactory compromises in the various tradeoffs shown previously in Fig. 3*.

The manner in which the two variables were displayed was important to the success of the system. The main hardware element of the display was the STOLAND Electronic Attitude Director Indicator (EADI) shown in Fig. 5. Safety margin information was presented along the vertical scale on the far left-hand side.

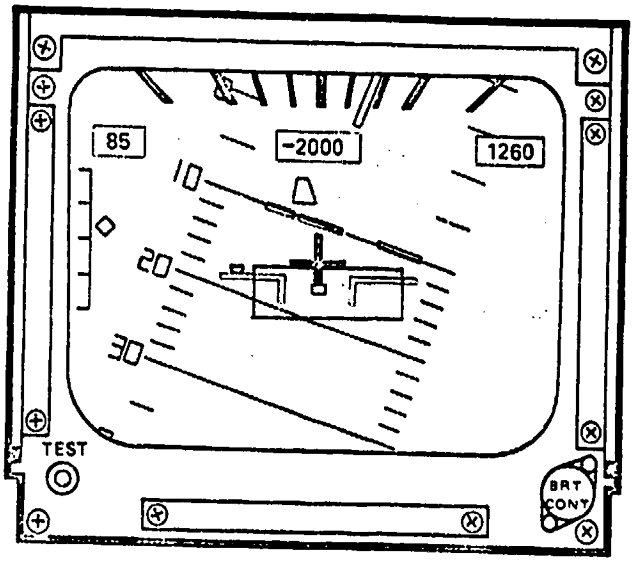

Figure 5. Overall EADI Presentation.

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* This value amounted to 10% safety margin change per degree pitch attitude change where the nominal operating point was at 100% allowable safety margin.

Details of the safety margin system presentation are described in Fig. 6. Note that the tracked variable is displayed directly on the moving pointer, but that the monitored variable is displayed as the distance between the moving pointer and a moving scale "floor." This configuration provided good relative emphasis on the two variables and did not confuse their respective roles in the pilot's mind.

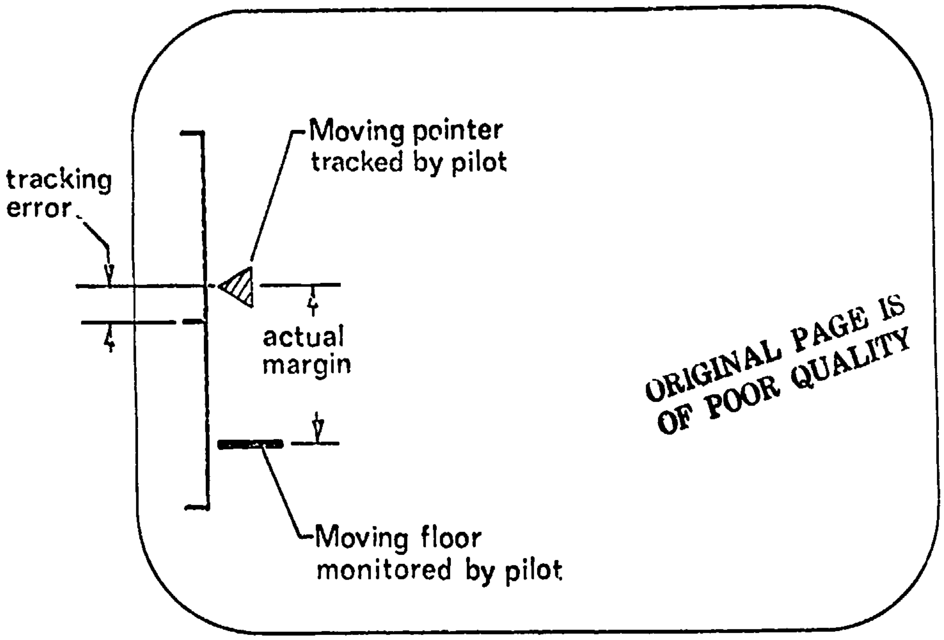

Figure 6. Details of Safety Margin System Display on EADI.

CONCLUSIONS

The study reported in this paper was successful in evolving a useful safety margin system and display for a powered-lift aircraft. The flight reference implementation found most effective involved a blend of the safety margin and a linear function of pitch attitude. This concept provided (i) an easily controlled variable, (ii) correct sensitivity to gusts, (iii) a guide to correct control action for obtaining good safety margin performance, (iv) acceptable performance in the presence of large atmospheric disturbances, and (v) the concept was relatively easily implemented. The main compromise resulting from the use of this concept was a reduction in available flight envelope in order to enhance certain controllability features. (The nominal operating point was approximately 5 knots faster than the minimum approach speed permitted by applicable safety margin criteria.) The envelope compromise was, however, controllable in a rational and predictable way by the flight reference weighting coefficient. Finally, the results of the study have provided the necessary groundwork for a flight investigation.

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