Configuration Management during Transition for a Powered-Lift STOL Aircraft

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Presented in this paper are the analytical and moving-base simulation results of a study to improve flight safety and operations of V/STOL-type aircraft. One of the more significant and novel aspects of the work accomplished has been the concept and implementation of a configuration management flight control system designed to take the guesswork out of, and improve the operational safety of, transition flight in the region from cruise to STOL.

Basic Problem

MANY powered STOL or VTOL aircraft have a redundant set of basic longitudinal controls, e.g., elevator, flaps, throttle, and thrust vector angle. This redundancy permits the aircraft to be trimmed for a given steady speed, angle of climb, and attitude in any one of a large number of control combinations, as depicted generically in Fig. 1. The bounds of this figure are either physical limits (e.g., maximum or minimum throttle, thrust vector angle, or speed-associated flap placards) or represent areas where flight safety or comfort is deficient (e.g., stall α, min θ). For some aircraft, additional limits due to buffet, deficient handling, etc., might be superimposed. Qualitatively similar (but quantitatively different) plots for each speed and path angle make up the totality of the trim space available. [Note that a given steady path angle is equivalent also to an instantaneous acceleration and a different path angle in accordance with the general trim condition $(T_x - D)/W \doteq \gamma + a_x/g = \text{const.}$]

The wide range of possible trim conditions inherent in the preceding picture seems to be highly desirable from the standpoint of enhanced operational flexibility. However, considering the available incremental performance, safety and comfort margins, handling characteristics, etc., about a given trim condition, much of the total available steady trim space is neither safely nor comfortably usable. A completely flexible approach to trim management therefore can result, at worst, in inadvertent, dangerously marginal conditions or, at best, in near-optimum, safe, high-margin conditions. To insure that the best possible trim conditions always are used and to prevent inadvertent incursions into marginal regions, it is advisable to narrow the available trim space to a "desirable" region, as depicted schematically in Fig. 2. Acknowledging the existence of, and then defining, the bounds for this desirable region is the basic problem at hand. Because the overall operational window and the enclosed desirable region change as a function of vehicle speed, plots similar to Fig. 2 can be made for several speeds. The desirable regions at each speed then can be connected to form a tube or corridor of desirable trim states (configurations), as depicted in the three-dimensional sketch in Fig. 3. Thus, a transition from 120 (for example) down to 60 knots can be made in a more or less optimum manner by staying within the corridor of desirable transitions shown in Fig. 3.

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Approach to the Problem

To implement this concept first requires that the chosen corridor have the best obtainable characteristics relative to some set of standards. The following list of desirable properties is suggested as appropriate for the transition "maneuver": 1) adequate closed-loop small-perturbation control about all trim operating points with a uniform piloting technique to permit positive control of progression (or regression) through the transition trim states; 2) adequate $\pm\Delta\gamma$ (or Δa_x) control; 3) only small changes in trim attitude and angle of attack (the first to ease the piloting workload problem, and the second to preserve stall margin); and 4) monotonic trim configuration settings as a function of speed, if possible.

A few words of explanation are necessary to bring the foregoing pilot-centered considerations into perspective. Adequate closed-loop path control at each operating point can be achieved best if more or less fixed handling characteristics are provided. Proper variation in the configuration (i.e., actual control of the lift/drag and thrust inclination) provides a direct means of setting the trim performance. Conversely, these same performance characteristics (i.e., lift and drag properties) govern the path dynamics and closed-loop control, since a strong relationship exists between performance and key closed-loop path control parameters. This relationship is reasonably well documented (e.g., Refs. 1-3);

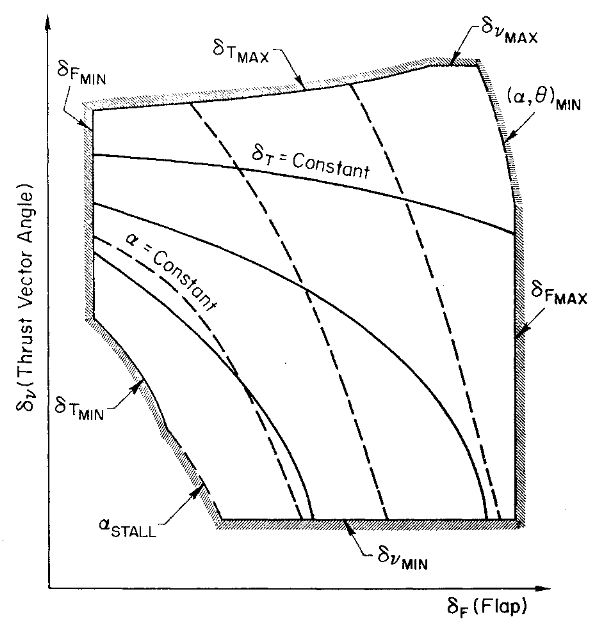

Fig. 1 Generic plot of operational window for constant speed and flight-path angle (or a_x).

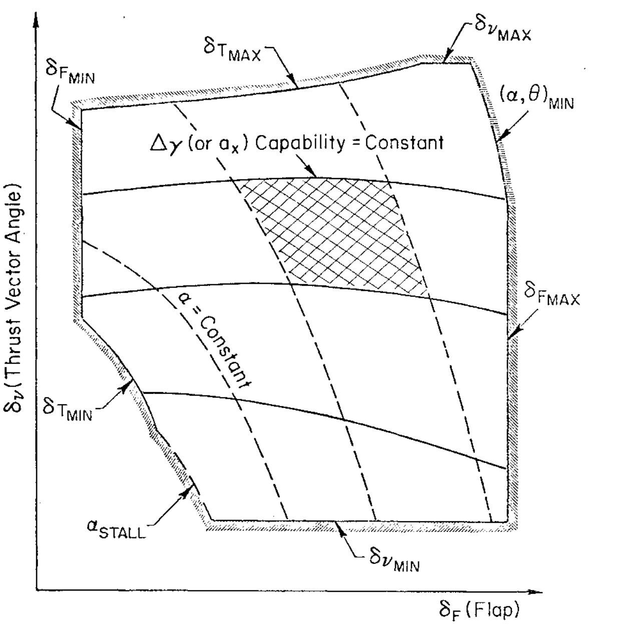

Fig. 2 Generic plot of desirable configurations within the overall operational window.

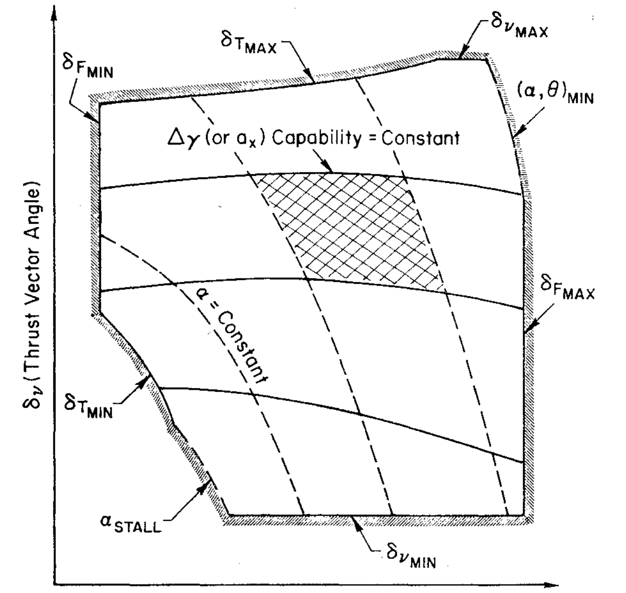

Fig. 4 Suggested region of desirable configurations within the overall operational window.

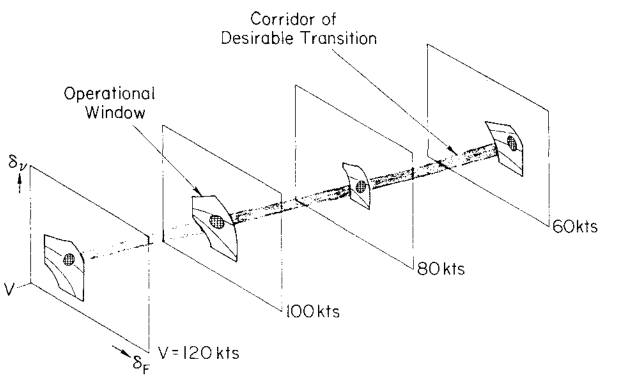

Fig. 3 Generic view of available and desirable trim states.

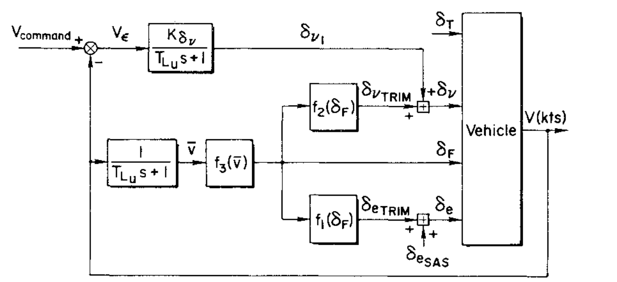

Fig. 5 Schematic block diagram of automatic configuration and speed control system (actuator lags are now shown). Note: f_1, f_2, and f_3 are functions derived from trim curves (for 120>60 kts).

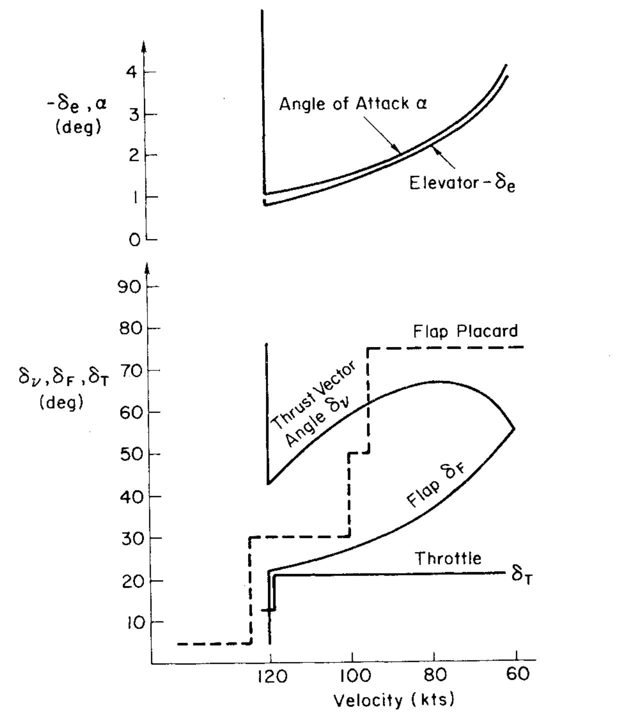

Fig. 6 Vehicle configurations during conversion to STOL and nominal transition to $\gamma = a_x = 0$. (Note that conversion to STOL at 120 knots occurs at essentially constant elevator position.)

therefore, it will not be discussed here. However, Ref. 1 is recommended for those readers who are not familiar with this tie of path dynamics and basic aircraft performance features. In item 4, a form of static stability is inferred by having the monotonic relation between trim speed and configuration (i.e., configuration stability). This provides the pilot with a practical means of speed reference to insure safety margin and/or to ease his workload.

Using the preceding properties as a basis, the cross-hatched region in Fig. 4 is suggested as a region of desirable configurations. When such a region is defined at each speed during the transition, then the task is one of selecting a single path along the three-dimensional tube (corridor) which satisfies the desirable properties just listed. This single path then becomes the nominal trim schedule during a transition.

It can be appreciated that the imposition of a "nominal" trim schedule does not detract in any way from the flexibility inherent in the basic set of redundant controls. Rather, it provides a framework of standard activity and responses which is desirable in itself, and especially so in view of the resulting near-maximum performance and other good flight qualities. The second requirement in implementing the concept is to insure that configurations remain within the desired corridor.

Solution to the Problem: Automatic Configuration (and Speed) Control System

In addition to insuring that the desired configuration will be achieved at each speed, the ultimate pilot relief from trim

Table 1 Control improvement evaluations

Flight control mode	Pilot rating				Remarks
	Still air		Wind shear & gust		
	Pilot A	Pilot B	Pilot A	Pilot B	
Manual basic airplane	5	...	7	...	Manual control in wind shear environment is an unacceptable situation.
Automatic configuration management	1-2	2-3	3	3	In still air, pilot B rated the transition (from 120 to 60 knots) as 2, and the conversion to STOL (140-120) as 3.

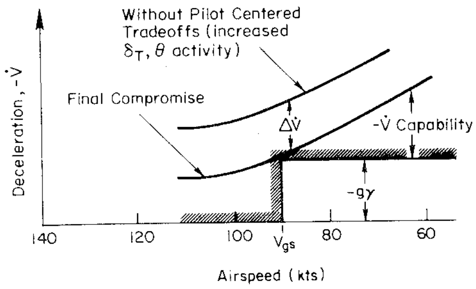

Fig. 7 Effect of glide path angle of deceleration capability.

management workload also is achieved by utilizing an automatic trim management/command system. Up to this point, the discussion has been quite general. However, it is now convenient to refer to a specific example. The example used here is the augmentor wing jet STOL research airplane (a modified C-8 Buffalo). It is emphasized that a VTOL or tilt wing or other example also would be appropriate, but the analysis was carried out for the augmentor wing airplane, so that data are readily available (Refs. 4,5).

In any event, the sequential considerations of importance in developing an automatic configuration control system are 1) the flap and interconnected thrust vector control should be programmed as a function of speed; 2) because premature flap deflections cause "ballooning," it is desirable for the flap to lag, rather than lead, speed changes; 3) flap actuation is slower than thrust vector actuation, and therefore, use the flap to drive the thrust vector control (for trim); 4) to complete the configuration management picture, use the flap also to drive the elevator (for trim); and 5) speed regulation and command (acceleration/deceleration) is accomplished best with a direct X-force (thrust or drag) device, which in this case is a perturbation in the thrust vector angle (when the thrust is nominally up).

In summary, for trim, drive the flap with speed, and thrust vector and elevator with the flap. (This will insure a desirable vehicle configuration at all speeds, and there will be no ballooning.) For speed control, use the velocity error to additionally bias the thrust vector. This control logic is depicted as

$$V_c \rightarrow V_\epsilon \rightarrow \Delta\delta_\nu \rightarrow \dot{V} \rightarrow V \rightarrow \delta_F \begin{matrix} \nearrow \delta_{e_{\text{trim}}} \\ \searrow \delta_{\nu_{\text{trim}}} \end{matrix}$$

The system block diagram is shown in Fig. 5.

In this automatic control mode, the pilot flies with elevator and throttle much the same as he would with a conventional frontside airplane. That is, altitude is controlled with attitude, and sink rate trim is controlled with throttle. The control system operates the thrust vector angle (to provide acceleration and deceleration, as well as trim), the flap (to keep trim angle of attack within an acceptable range), and elevator (for trim), as shown schematically in the block diagram of Fig. 5. Thus, the control system not only controls speed, but it also controls the vehicle configuration to insure that it is within a "good" region of the overall window of possible configurations. To initiate or stop transition, the pilot has only to set a speed-command "bug" to the desired speed. Plots of the three controls operated by the automatic control system (nominal trim elevator, flap, and thrust vector angle), along with the one trim control operated by the pilot (throttle) and the resulting trim angle of attack, are presented in Fig. 6.

Simulation Plan

A basic simulation experiment was developed to investigate and assess the possibilities for improved trim management and glide slope control on the NASA Ames FSAA facility.

In addition to accomplishing the level flight transition maneuver to 60 knots, the pilot also was required to acquire and track the —7.5° glide slope. The transition "Maneuver" itself was, furthermore, to be subjected to detailed examination as to controllability. That is, the pilot's ability to stop transition at any point, hold speed or return to a higher speed condition, or proceed with speed reduction, etc., was to be investigated and assessed. Table 1 provides a succinct summary of the significant comparison obtained.

Conclusions

The basic conclusions, supported by both analysis and simulation, are as follows:

1) A four-control (δ_e, δ_F, δ_ν, δ_T) manual situation results in excessive pilot workload.

2) The concept of using control crossfeeds to constrain the possible vehicle configurations (as well as to simplify the piloting task) was confirmed as useful and desirable. It is especially effective when used also to eliminate relatively unsafe configurations and improve operational performance (e.g., it is noted that throughout the transition there are adequate margins in angle of attack, throttle, and thrust vector angle available for maneuvering the aircraft should the need arise).

3) The automatic system was validated as being very desirable. It made the vehicle "fly like an airplane," and it made it easy to control flight path with either attitude or throttle.

Appendix: Advanced Application of Configuration Management Control

Results of a follow-on study are noted briefly here. In this study, the performance capabilities of the airplane were pushed to the limits in an attempt to achieve a curved, decelerating, descending trajectory. The task was carried out successfully, but at the expense of some compromises not required for the level flight transition. Specifically, the primary source of the problem lies in the limited capability of the aircraft to decelerate on the glide path. The total acceleration along the velocity vector, $\dot{V}$, is given as

$$\dot{V} = a_x - g\gamma$$

where a_x can be achieved with power, flap, and thrust vector angle changes. Note that, in level flight, all of the deceleration capability goes directly into speed changes, whereas in descending flight (negative γ) the maximum $-\dot{V}$ capability is decreased by $g\gamma$. This is shown graphically in the generic sketch in Fig. 7.

Figure 7 indicates that improved performance can be obtained if the pilot-centered requirements are ignored. That is, increased deceleration capability can be achieved via large changes in thrust and pitch attitude. The penalty is a significant increase in pilot workload and corresponding degradation in pilot opinion. The fundamental tradeoff centers about the ability to achieve an acceptable level of deceleration capability at glide slope intercept without incurring large variations in pitch attitude and thrust, and to maximize, as much as possible under such constraints, the allowable speed for glide slope intercept, V_{gs}. The final compromise does this for nominal winds (head wind less than 25 knots). However, in the presence of a tailwind, $-\gamma_{\text{eff}}$ is increased, and the $\dot{V}$ margin is reduced to the point where the aircraft will not decelerate below V_{gs} on the glide path. A practical solution then is to intercept the glide slope at the lower speed when this condition exists.

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