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DEVELOPMENT OF CONTROL STRATEGIES FOR SAFE MICROBURST PENETRATION:

A PROGRESS REPORT

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REVIEW OF WORK DONE PRIOR TO SEPTEMBER 1983

A microburst, a downburst of horizontal extent less than 3 miles, consists of a vertically descending column of air that spreads out horizontally as it hits the ground. A penetrating aircraft first encounters a headwind which causes a pitch-up and a rise above the flight path. Then it experiences a shear of the headwind to a tailwind along with a downdraft, both of which cause it to fall below the glide path.

A nonlinear simulation of the longitudinal equations of motion of a Jet Transport aircraft that includes wind inputs was used to study the transient response to a microburst. These were compared to plots of the aircraft's frequency response to wind inputs as generated from a linearized model.

Various loop closures were studied using root locus analysis and the above-mentioned frequency response and transient response plots. Feedback of air-relative specific energy rate to the throttle yielded improvements in frequency response, but not in transient response to microburst due to throttle saturation. Feedback of $\bar{q}\alpha$ (the normal load factor) or airspeed (with wrong sign) to the elevator yielded improvements both in frequency response and in transient response to microburst.

- MICROBURST WIND SHEAR HAZARD
- NONLINEAR LONGITUDINAL SIMULATION
- BODE PLOTS OF FREQUENCY RESPONSE TO WIND INPUTS
- EFFECTS OF VARIOUS LOOP CLOSURES
    - → ROOT LOCI
    - → FREQUENCY RESPONSE
    - → NONLINEAR TRANSIENT RESPONSE

WORK DONE SINCE SEPTEMBER 1983

A single-engine, propeller-driven, general-aviation model was incorporated into the nonlinear simulation and into the linear analysis of root loci and frequency response. Full-scale wind tunnel data provided its aerodynamic model, and the thrust model included the airspeed dependent effects of power and propeller efficiency.

Also, the parameters of the Jet Transport model were changed to correspond more closely to a Boeing 727.

In order to study their effects on steady-state response to vertical wind inputs, altitude and total specific energy (air-relative and inertial) feedback capabilities were added to the nonlinear and linear models.

Multiloop systems design goals were defined. Attempts were made to develop controllers which achieved these goals.

- INCORPORATION OF GENERAL AVIATION (GA) MODEL
- IMPROVEMENT OF JET TRANSPORT (JT) MODEL
- CONSIDERATION OF ALTITUDE AND TOTAL ENERGY TYPE FEEDBACK
- ATTEMPT AT MULTILOOP CONTROLLER DESIGN

EFFECTS OF ALTITUDE/ENERGY FEEDBACK

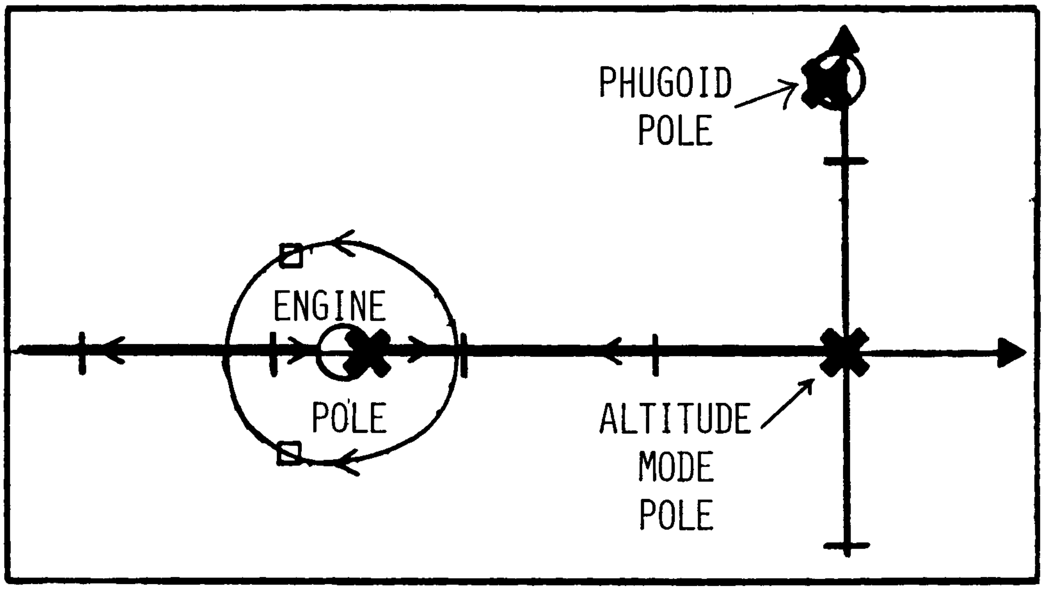
In the literature one finds the altitude error being fed back to the elevator to attenuate response to vertical wind inputs. For the purposes of this study, this does not work well due to stability limitations imposed by the non-minimum phase relation between the elevator and the altitude and by the effects of being on the backside of the power curve.

Feedback of total air-relative specific energy to the throttle satisfactorily stabilizes the neutrally stable altitude mode. Addition of energy rate feedback to the loop provides further stability improvements and improves transient response to microbursts by adding lead information.

- ALTITUDE-TO-ELEVATOR LOOP
- TOTAL AIR-RELATIVE SPECIFIC ENERGY-TO-THROTTLE LOOP
- TOTAL AIR-RELATIVE SPECIFIC ENERGY-PLUS-TOTAL AIR-RELATIVE SPECIFIC ENERGY RATE-TO-THROTTLE LOOP

ROOT LOCUS, PHUGOID PORTION, H_a-PLUS-$\dot{H}_a$-TO-δT FEEDBACK

Although the rigid-body longitudinal motion of the aircraft and the engine dynamics and altitude feedback yield a sixth-order system, the root locus for feedback of specific energy to throttle resembles that of a second-order system. This is because total specific energy varies little with phugoid or short period oscillations. By adding specific energy rate feedback such that the new zero is just to the left of the engine dynamics pole, the root locus resembles that of a first-order system and desirable stability characteristics can be achieved.



MULTI-LOOP CONTROLLER DESIGN

Examination of open-loop frequency response and transient response to microbursts yielded three main results.

1. Open-loop aircraft response to the head/tail wind shear of a microburst is extreme when the characteristic frequency of the microburst is near that of the phugoid's natural frequency.
2. Open-loop response to the head/tail wind shear is still unacceptably high for excitation frequencies below that of the phugoid.
3. Response to the down draft resembles that of an integrator responding to a finite-width impulse and can be unacceptably high for the open-loop case and typical microbursts.

The stated design criteria were developed with alleviation of these effects in mind.

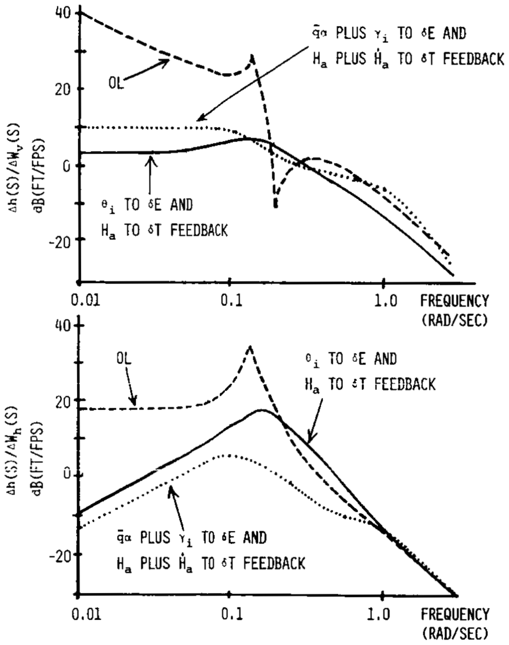
The first of the two control laws attempts to satisfy the first two design criteria, while the second control law does a reasonable job of satisfying all three criteria, provided the aircraft does not stall.

- DEVELOPMENT OF WIND SHEAR ATTENUATION DESIGN CRITERIA
  - → INCREASE IN PHUGOID DAMPING
  - → ELIMINATION OF INTEGRATION RESPONSE TO VERTICAL WIND INPUT
  - → REDUCTION OF LOW FREQUENCY RESPONSE TO HORIZONTAL WIND INPUTS

- MULTI-LOOP-CONTROLLERS
  - → θ_i-TO-δE AND H_a-TO-δT
  - → $\bar{q}\alpha$-PLUS-γ_i-TO-δE AND H_a-PLUS-$\dot{H}_a$-TO-δT

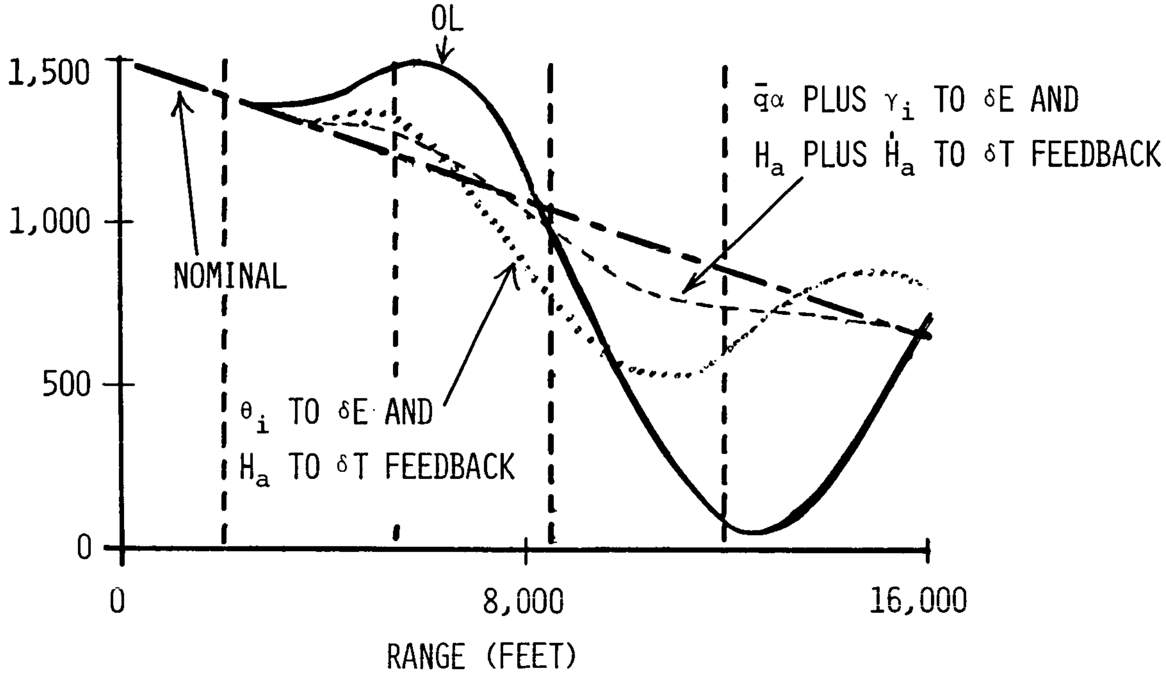
ALTITUDE FREQUENCY RESPONSE TO HORIZONTAL AND VERTICAL WIND INPUTS WITH $\bar{q}\alpha$-PLUS-γ_i-FEEDBACK TO-δE AND H_a-PLUS-$\dot{H}_a$-FEEDBACK TO δT

The effects of two multi-loop control laws on frequency response, both to vertical and to horizontal wind inputs, are shown here in comparison with the open-loop case. The feedback of H_a-to-δT changes the order of the system, stabilizing the altitude mode pole and raising the low-frequency slopes of both plots by 20 dB/decade. Addition of an $\dot{H}_a$-to-δT loop further lowers the low-frequency response to horizontal wind input. Feedback of θ_i-to-δE or $\bar{q}\alpha$-plus-γ_i-to-δE eliminates the resonant peak at the phugoid natural frequency. Feedback of $\bar{q}\alpha$-plus-γ_i-to-δE lowers the natural frequency of the phugoid, thus lowering the peak response to horizontal wind inputs, but this loop also raises the low-frequency response to vertical wind inputs because of the effects of being on the backside of the power curve.



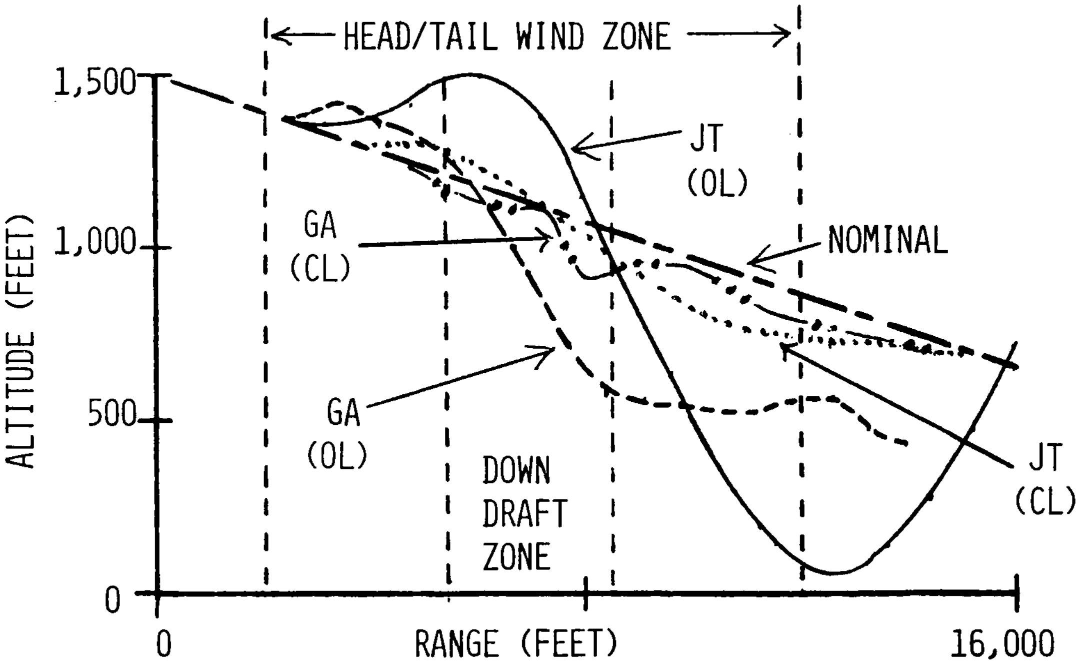
TRANSIENT RESPONSE TO MICROBURST WITH $\bar{q}\alpha$-PLUS-γ_i-TO-δE FEEDBACK AND H_a-PLUS-$\dot{H}_a$-TO-δE FEEDBACK

These simulation results of approach trajectories through a microburst tuned to the jet transport phugoid show that the control law which satisfied all three design criteria also yielded the best trajectory tracking performance in transient response to a microburst. Neither control law yielded as low a transient response as was predicted by the frequency response plots because throttle saturation occurred in both cases.



COMPARISON OF OPEN-LOOP AND CLOSED-LOOP TRANSIENT RESPONSE TO MICROBURST FOR TWO AIRCRAFT

These simulation results of approach trajectories through a microburst compare both open-loop and closed-loop curves for both the general-aviation and jet transport aircraft. The general-aviation response to the head/tail wind shear is lower in both the open-loop and closed-loop cases because this microburst is tuned to the jet transport's phugoid, and therefore forces the general-aviation aircraft at a frequency far below its phugoid natural frequency. The general-aviation response to the downdraft, however, is more severe because of its lower wing loading and its lower nominal velocity (longer time in the downdraft). In the closed-loop case, this causes the general-aviation aircraft to stall because of the $\bar{q}\alpha$-plus-γ_i-to-δ_E feedback loop.



CONCLUSIONS

Although exact prediction of transient response using frequency response plots is not possible due to control saturation and the steady-state nature of the plots, frequency response to wind shear is a useful tool for control law evaluation. Because throttle saturation and aircraft stall limits are significant factors in determining microburst penetration capability, nonlinear simulation of microburst encounter is essential to the evaluation of control laws. The best multi-loop control law tested to date incorporated both energy management relative to the air mass via throttle and a pitch-up response to decreasing airspeed.

- CORRELATION BETWEEN BODE FREQUENCY RESPONSE PLOTS AND SIMULATION RESULTS
- SIGNIFICANCE OF THROTTLE SATURATION AND AIRCRAFT STALL NONLINEARITIES TO PERFORMANCE LIMITS
- NEED FOR NONLINEAR SIMULATIONS
- IMPORTANCE OF ENERGY MANAGEMENT RELATIVE TO THE AIR-MASS FOR TRAJECTORY TRACKING
- BENEFIT OF PITCH-UP RESPONSE TO DECREASING AIRSPEED

PLANNED FUTURE WORK

The current microburst model has only the basic features of the headwind, downdraft, and tailwind sequence. Better models, based upon meteorological data, are becoming available and should be used to evaluate final designs.

There remains some question as to the validity of the point-aircraft, quasi-steady aerodynamics model which is used by most researchers in this field. Again, a thorough validation of the model must be made before any final conclusions are reached.

Wind shear estimation and cancellation of wind shear-induced forces and moments in a feed-forward control law are possibly useful approaches to safer microburst encounter.

As yet, the best possible performance of an aircraft during microburst encounter has not been determined. This calculation is a lengthy, but straightforward application of nonlinear optimal control theory. It will demonstrate the limits of the performance envelope and will possibly lead to the development of previously unknown techniques for safe microburst penetration. Also stochastic optimal control techniques may be useful to the development of practical control laws which attenuate the aircraft response to a microburst.

- IMPROVE MICROBURST MODEL
- CHECK VALIDITY OF QUASI-STEADY, POINT AERODYNAMIC MODEL
- STUDY FEED-FORWARD CONTROL
    1. WIND SHEAR ESTIMATION
    2. GENERALIZED FORCE CANCELLATION
- APPLY OPTIMAL CONTROL THEORY
    1. TRUE OPTIMUM - REQUIRES KNOWLEDGE OF FUTURE DISTURBANCE
    2. PRACTICAL OPTIMUM - DISTURBANCE TREATED AS RANDOM