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Fuzzy Logic Decoupled Lateral Control for General Aviation Airplanes

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ABSTRACT

It has been hypothesized that a human pilot uses the same set of generic skills to control a wide variety of aircraft. If this is true, then it should be possible to construct an electronic controller which embodies this generic skill set such that it can successfully control different airplanes without being matched to a specific airplane.

In an attempt to create such a system, a fuzzy logic controller was devised to control aileron or roll spoiler position. This controller was used to control bank angle for both a piston powered single engine aileron equiped airplane simulation and a business jet simulation wich used spoilers for primary roll control. Overspeed, stall and overbank protection were incorporated in the form of expert systems supervisors and weighted fuzzy rules.

It was found that by using the artificial intelligence techniques of fuzzy logic and expert systems, a generic lateral controller could be successfully used on two general aviation aircraft types that have very different characteristics. These controllers worked for both airplanes over their entire flight envelopes. The controllers for both airplanes were identical except for airplane specific limits (maximum allowable airspeed, throttle lever travel, etc.).

This research validated the fact that the same fuzzy logic based controller can control two very different general aviation airplanes. It also developed the basic controller architecture and specific control parameters required for such a general controller.

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1 INTRODUCTION

This project was performed as part of the National Aeronautics and Space Administration (NASA) Advanced General Aviation Transportation Experiment (AGATE) program. The purpose of the AGATE program is to reduce the manufacturing, training and proficiency costs associated with general aviation airplanes.

1.1 Flight Controls Research in the AGATE Program

One of the areas of funded research is the development of advanced flight controls concepts. The purpose of the flight controls research is to develop a control system that works in conjunction with advanced display systems to allow a pilot with minimal training to operate safely in instrument meteorological conditions.

There are three basic types of control systems to be examined. These are stability augmentation, attitude command and fully decoupled controls.

Stability augmentation involves altering the stability characteristics, usually by electronic means. A yaw damper is an example of this. These types of systems have had limited acceptance by the pilot community because they generally reduce maneuverability or create a feeling of "heaviness" in the controls.

An attitude command system has been shown to significantly reduce pilot workload, particularly in turbulence [1]. This is a system where the pilot commands airplane attitude. Using separate control surfaces, this system can be implemented as a combination fly-by-wire / mechanical control system where the pilot directly controls the mechanically driven surfaces while simultaneously commanding an attitude. The fly-by-wire surfaces are then deflected as required by a fly-by-wire system to achieve the commanded attitude. An advantage of this type of system is that the airplane can be landed with a failure in the fly-by-wire system. This advantage carries with it the liability that it requires the pilot to be trained to fly the airplane using only conventional control techniques as well as attitude command techniques.

The decoupled control system has been shown to significantly reduce pilot training time [2-4]. With this system the pilot commands climb rate, airspeed and turn rate. This system is a fly-by-wire system that does not readily lend itself to a mechanical backup. Also, to produce an airplane that requires less training time, it is highly desirable to teach the pilot only one control scheme. These two factors require that a decoupled flight control system be made highly reliable since its operation is critical to the safety of flight.

One of the problems with any fly -by-wire system is that it takes a significant amount of time and effort to tune the gains of the control system to match the response characteristics of the airplane. Also, a control system developed and tuned for a particular model cannot be expected to work on a different model even if the two models are very similar.

1.2 Fuzzy Logic as Applied to a Reusable Decoupled Flight Control System

A relatively new technique for controlling a plant through a feedback control loop is the use of fuzzy logic as developed through artificial intelligence research. A controller based on fuzzy logic is less sensitive to variations in the plant than a conventional controller [5-8]. This characteristic may enable a fuzzy decoupled control system developed on one airplane to be moved to another model with minimal retuning requirements. It may also eliminate the need for gain scheduling as a function of flight conditions.

Another artificial intelligence technique that fits well with fuzzy logic is an expert systems supervisor. This part of the controller can be programmed to provide control boundaries such as angle of attack and airspeed limits.

If a general flight control scheme such as the fuzzy / expert system described above can be perfected, then much of the development time and expense of matching an autopilot to a specific airplane can be eliminated [9 - 11]. With a reduction in development costs, a decoupled flight control system could be practical for general aviation airplanes. The implimentation of this type of system has the potential of greatly reducing the initial training and proficiency costs of operating personal aircraft. This potential reduction in training and proficiency costs was the motivation for this research.

1.3 The Goal of this Research

This work is based on the hypothesis that the control scheme described above is the means by which human pilots control aircraft. A flight instructor teaches the student the rule set (e.g. You're a little slow, add some power.) and simultaneously identifies the fuzzy membership functions (what 'a little slow' looks like and how much is 'some' power). After gaining experience in several types of aircraft, the pilot generalizes the rule set and membership functions such that he can control an unfamiliar airplane satisfactorily the first time he flies it. (As long as the machine generally responds like the other airplanes he has flown.) The expert knowledge is conveyed to the pilot via stall warning, knowledge of airspeed limits, etc.

Assuming this hypothesis is true, it should be possible to design a generic electronic flight control system based on fuzzy logic which can satisfactorily control any airplane which meets FAR part 23 or 25 handing characteristics requirements. The key to success is then extracting from a pilot and implementing in a computer the input sets, rule sets and output sets with sufficient accuracy and completeness that the electronic controller can control any general aviation airplane satisfactorily.

The purpose of this work was to demonstrate that a controller can be devised that can satisfactorily control a wide variety of FAR part 23 and 25 airplanes. Therefore this research will concentrate on controlling two airplanes that are at very different positions within general aviation - an 11 place 16,000 pound business jet (Beechjet), and a generic 6 place 2,500 pound retractable landing gear piston powered single engine airplane (Bonanza class). Even though this research did not validate the hypothesis, it did provide two initial and significant data points, and developed the basic controller architecture and specific control parameters required for such a general controller.

Since fuzzy logic control systems are nonlinear, the usual analysis tools associated with linear control system design could not be used. The analysis was therefore done using time histories of aircraft simulations being controlled by the controllers developed in this project.

Using a simulation of a business jet, a fuzzy logic controller was developed to provide decoupled control of the lateral axis. This system was designed to follow a bank angle command. It also provided limited envelope protection (maximum allowable bank angle, and worked together with the stall and overspeed protection systems). After the controller was developed on the business jet it was moved to the single engine piston airplane and its performance evaluated on that airplane.

1.4 Research Covered by this Report

This report is a continuation of the longitudinal activities discussed in NASA CR-201639 [12]. Reference 12 contains background information, a brief tutorial on fuzzy logic, a discussion of the simulations used and a description of the longitudinal control architecture. This report contains the lateral directional architecture and the required changes to the longitudinal controllers to make them work smoothly with the lateral controller.

2 BANK ANGLE CONTROLLER

Initially, a turn rate command following controller was implimented. However, it was found while working with the jet simulation that at high true airspeeds, the controller produced roll rates that were considered unacceptable to passengers in nominally straight and level flight. This characteristic was verified in flight test by a human pilot using turn rate only to maintain wings level at high speed. The conclusion from this experiment was that using turn rate as the feedback parameter would not produce an acceptable controller.

Since turn rate is a function of bank angle and true airspeed by the relationship $\dot{\psi} V = g \tan\phi$ where $\dot{\psi}$ is turn rate, g is acceleration due to gravity, V is true airspeed and ϕ is bank angle, it can be seen that a controller which tracks a bank angle command is equivalent to a controller which commands turn rate times velocity. In other words, a bank angle tracking controller is equivalent to a controller which tracks turn rate but reduces its sensitivity as speed increases.

2.1 Controller Architecture

A block diagram of the bank angle controller is shown in figure 1.

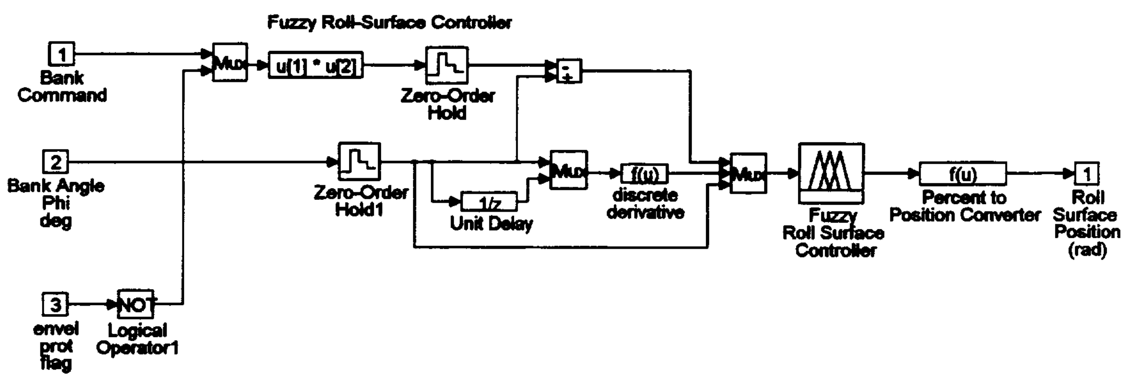


Figure 1. Bank angle controller architecture.

Inputs to this controller were commanded bank angle, actual bank angle and an envelope protection flag generated by the elevator controller to signal that either stall protection or overspeed protection is currently being exercised.

The envelope protection flag comes into this controller as a 0 for normal flight or a 1 if the elevator controller is in an envelope protection mode. The signal gets inverted and then multiplies the bank angle command. Thus, the bank angle command is unaffected for normal flight, but forces a wings level command (0 bank angle) when envelope protection is required.

Both the bank command and the bank angle were fed into a digitizer with a 0.05 second update rate. This sample rate was chosen because it is the same rate used by the elevator controller (Reference 12 pages 21 and 22) and since the longitudinal dynamincs are faster than the lateral dynamics it is fast enough.

The digitized bank error, roll rate and bank angle are then fed into the fuzzy logic controller which put out a roll control surface position command (spoiler for the jet or ailerons for the piston simulation). Overbank protection is handled inside the fuzzy controller.

2.2 Fuzzy Controller

The fuzzy inference engine has three inputs -- bank error, roll rate and bank angle. The input sets for these three parameters are shown in figures 2, 3 ,4 and 5. Figure 6 shows a list of the rules and the associated output singletons. Figure 7 shows the resulting three dimensional control surface from the fuzzy inference engine for bank angle error and roll rate.

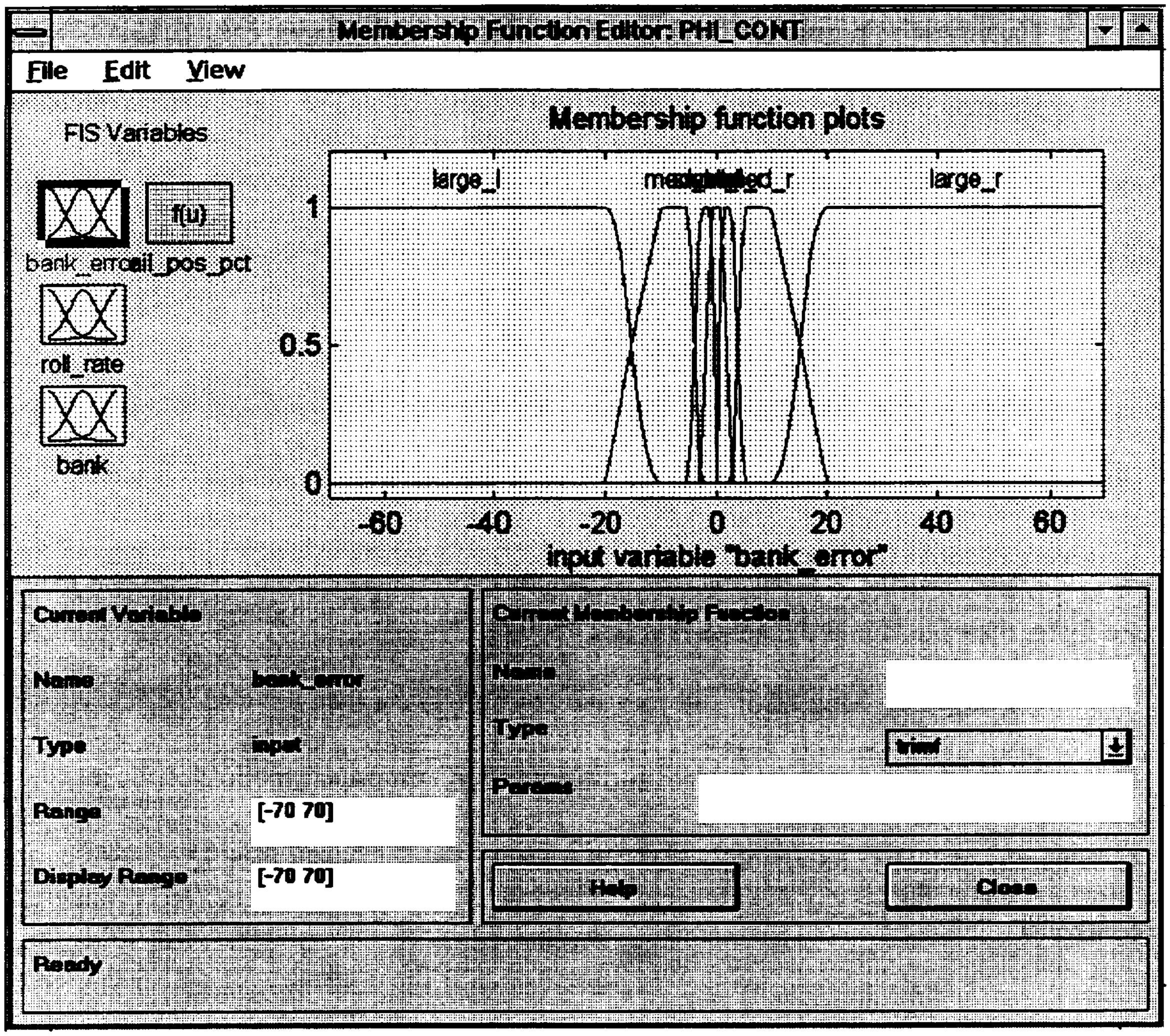


Figure 2. Fuzzy input sets for error in bank command (overall view).

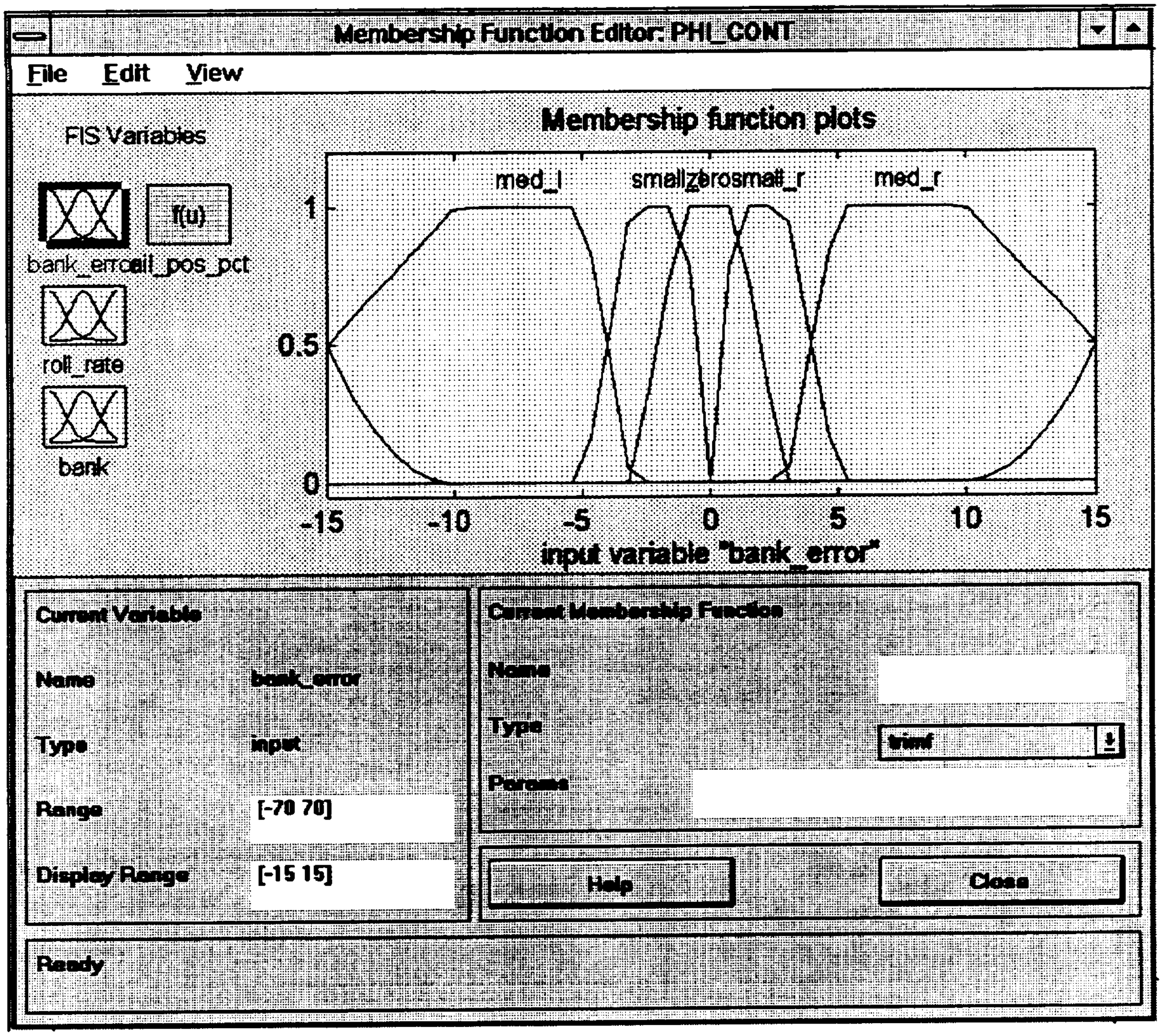


Figure 3. Fuzzy input sets for error in bank command (expanded view).

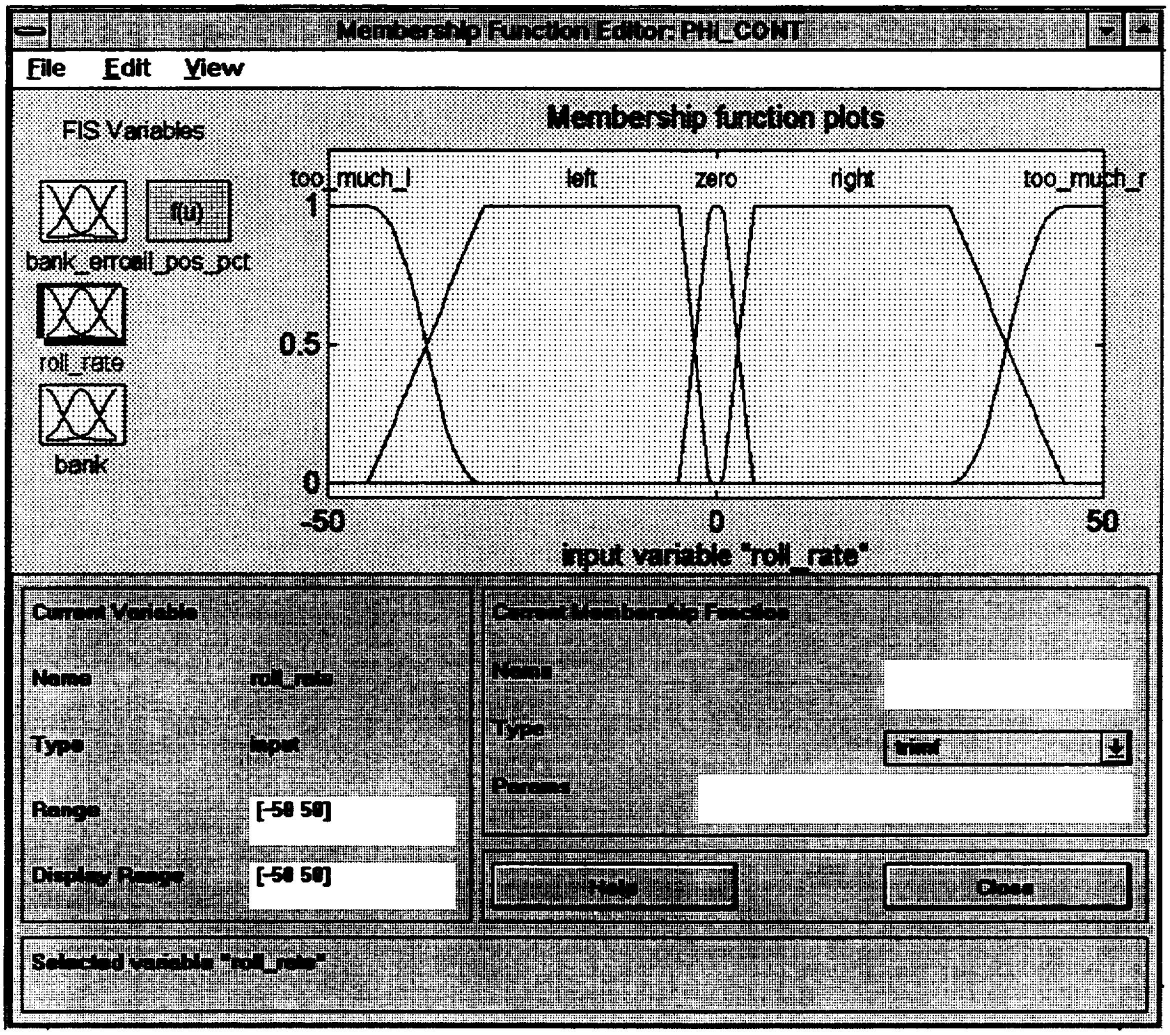


Figure 4. Fuzzy input sets for roll rate.

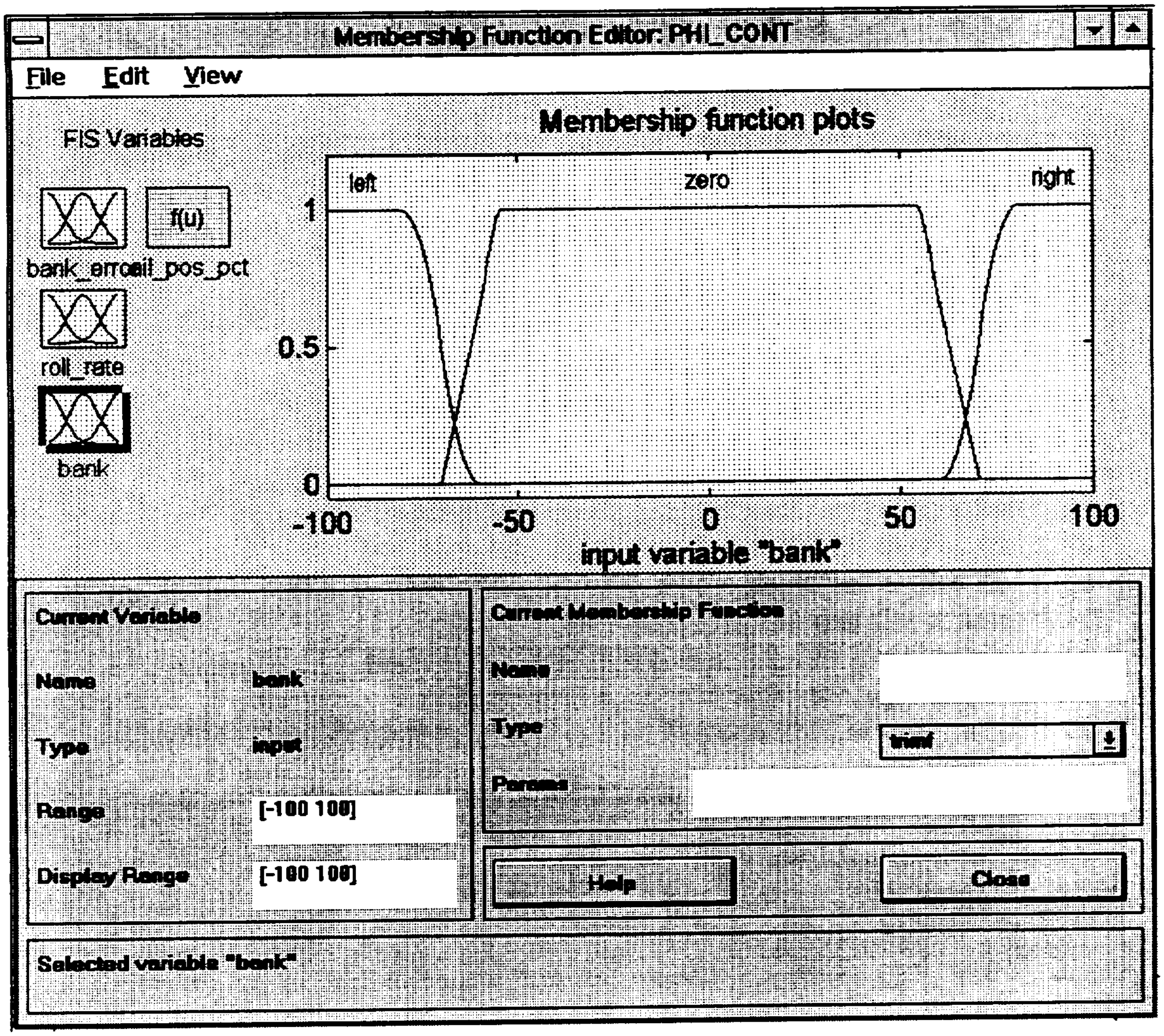
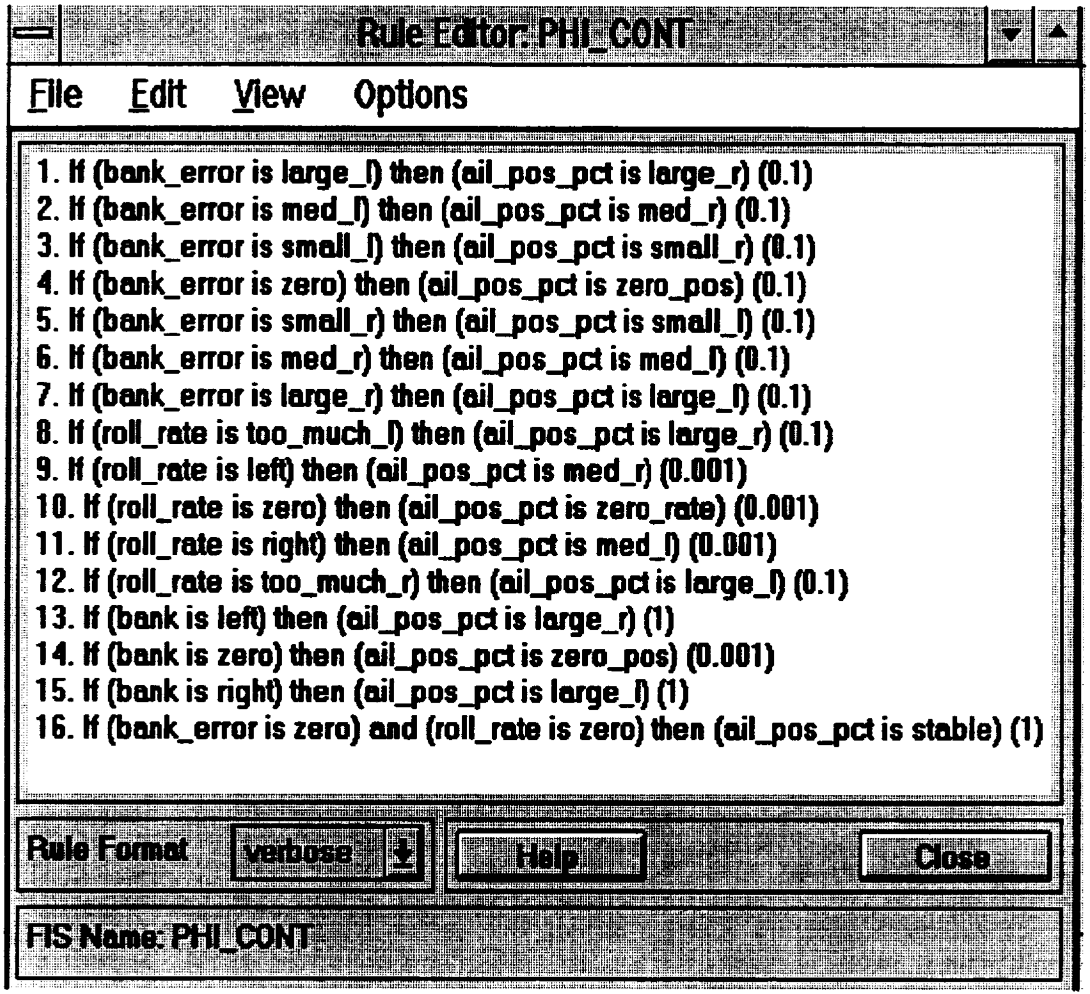


Figure 5. Fuzzy input sets for bank angle.



Output singletons:

$$\mathrm{large\_r} = -100 \qquad \mathrm{large\_r} = -100$$
$$\mathrm{med\_r} = \dot{\phi} - 30 \qquad \mathrm{med\_r} = \dot{\phi} - 30$$
$$\mathrm{small\_r} = 2\phi + \dot{\phi} - 5 \qquad \mathrm{small\_r} = 2\phi + \dot{\phi} - 5$$
$$\mathrm{zero\_rate} = 2\dot{\phi}$$
$$\mathrm{zero\_pos} = 5\phi + \dot{\phi}$$
$$\mathrm{stable} = 5\phi + \dot{\phi}$$

Figure 6. Output rules for the bank angle controller. The number to the right of each rule is a relative weighting parameter. All inputs are degrees, all outputs are percent roll control surface travel.

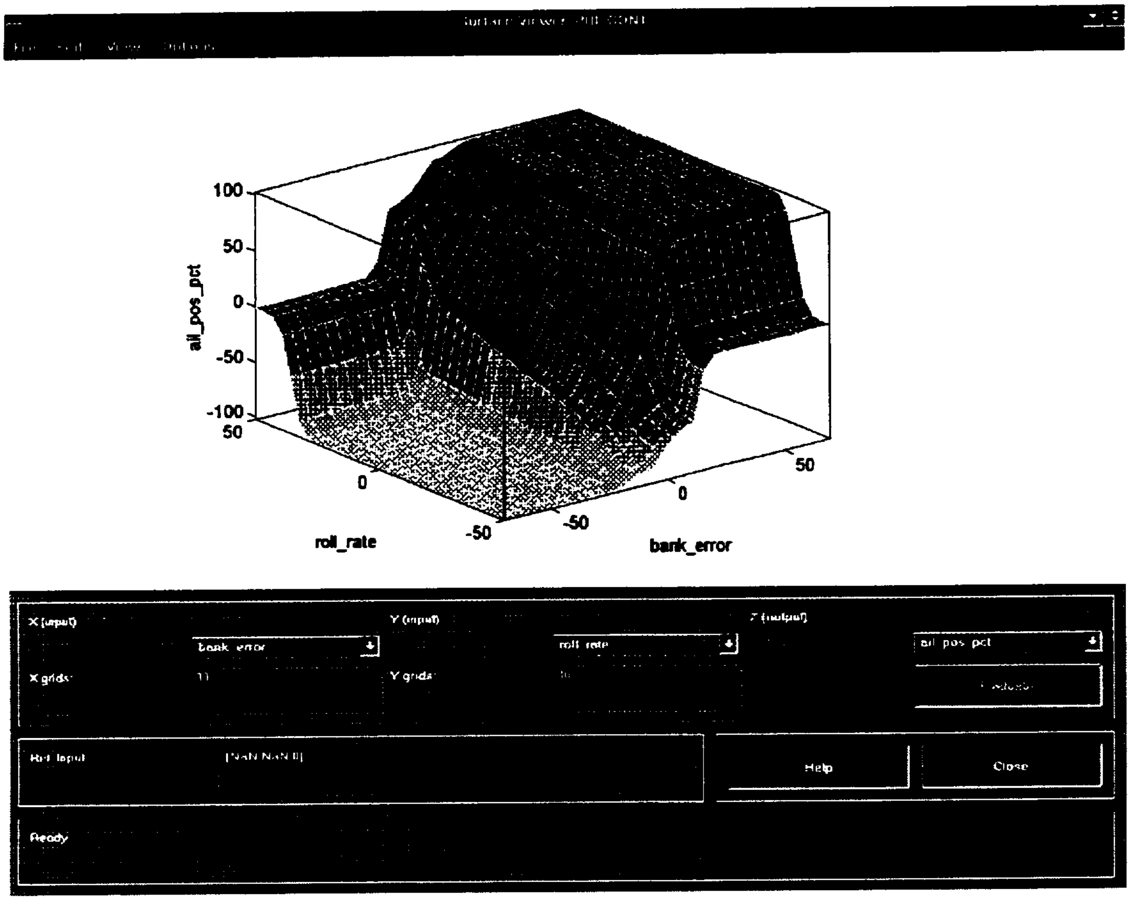


Figure 7. Resulting control surface from the fuzzy inference engine for the roll controller.

The fuzzy input set boundaries were chosen based on the author's experience flying various types of airplanes. Introspection revealed that when zero bank angle is desired and a small bank angle is observed, the pilot tends to input a correction to the control wheel that is proportional to the bank angle ($\delta_{Aileron} = k\ \phi$). It is unknown whether that function is linear or not (it probably varies from pilot to pilot). However it was assumed that it is at least close to linear and therefore a linear function was implemented.

The controller was first examined using the jet simulation. Running the simulation revealed that overshoots occurred when bank error only was used as a feedback parameter. Therefore roll rate was also added to increase roll damping.

Since the jet uses spoilers for roll control, rolling moment due to spoiler position is non-linear, and there is a lag between spoiler movement and roll moment generation. Also, since this airplane has moderate wing sweep, there is strong roll/yaw coupling at low speeds. In addition, this airplane has weak yaw damping at high altitude (a characteristic of most jets) so a yaw damper is required. Since for normal flight in this airplane a yaw damper is required, a simple yaw damper was added to the simulation. A block diagram of this yaw damper is shown in figure 8. No attempt was made to optimize or tune this yaw damper.

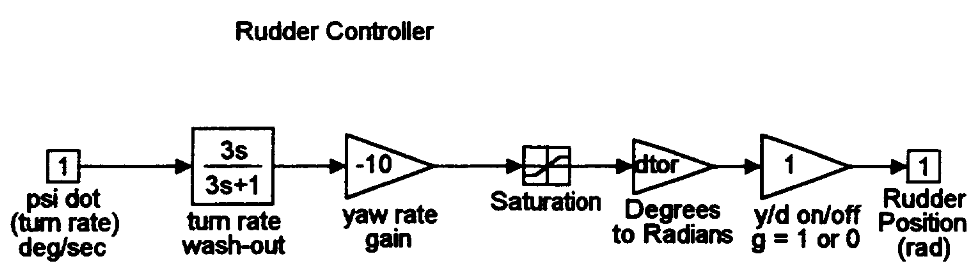


Figure 8. Yaw damper used for the jet simulation.
The saturation block limits rudder travel to ± 10 degrees.
The turn rate washout filter has a time constant which equates to 20 seconds per cycle.

The controller was implemented in the single engine simulation and worked satisfactorily the first time. The airplanes from which the single engine simulation were derived do not need a yaw damper so it was not installed in the simulation.

Overbank protection is provided within the fuzzy rule set for this controller instead of as a separate block as was done for the other controllers. This was done by weighting the rules relative to each other. As shown in figure 6, the rules that fire for "bank is left" and "bank is right" have a weighing of 1 where most of the rest of the rules have a weight of 0.1. As figure 5 shows, the "bank is left" and "bank is right" rules do not fire until the bank angle exceeds 60 degrees. Since the only other rule with a weight of 1 is "bank error is zero and roll rate is zero" and it is expected that the controller will be limited to sending commands of less than 60 degrees, the high bank and zero bank error rules will never fire at the same time. The effect of providing overbank protection in this way is that a smooth transition can be done between the protection action and normal control action, thus mitigating the effects of "automatic mode changes".

The other rule with a weight of 1 is the "bank error is zero and roll rate is zero" rule. This rule was given an overriding weight to guarantee that it is essentially the only control law in effect when the airplane is nominally in level flight.

The rules with a weight of 0.001 were created as place holders to cause a rule to fire for every fuzzy input set (this is a requirement of the development software being used for this project, but is not a general fuzzy logic requirement). They have such a low relative weight that they are always insignificant.

3 REQUIRED CHANGES TO THE PLA CONTROLLER

The power lever angle (PLA) controller was changed to facilitate smoother operation during turns. As bank angle increases the power required to maintain altitude and airspeed increases. An experienced pilot makes an initial guess at a power increase as he rolls into a turn. The amount of the increase is based on the starting bank angle and the desired final bank angle. In an attempt to copy this function, the "Predictive PLA for banking" block was added as shown in figures 9, 10 and 11.

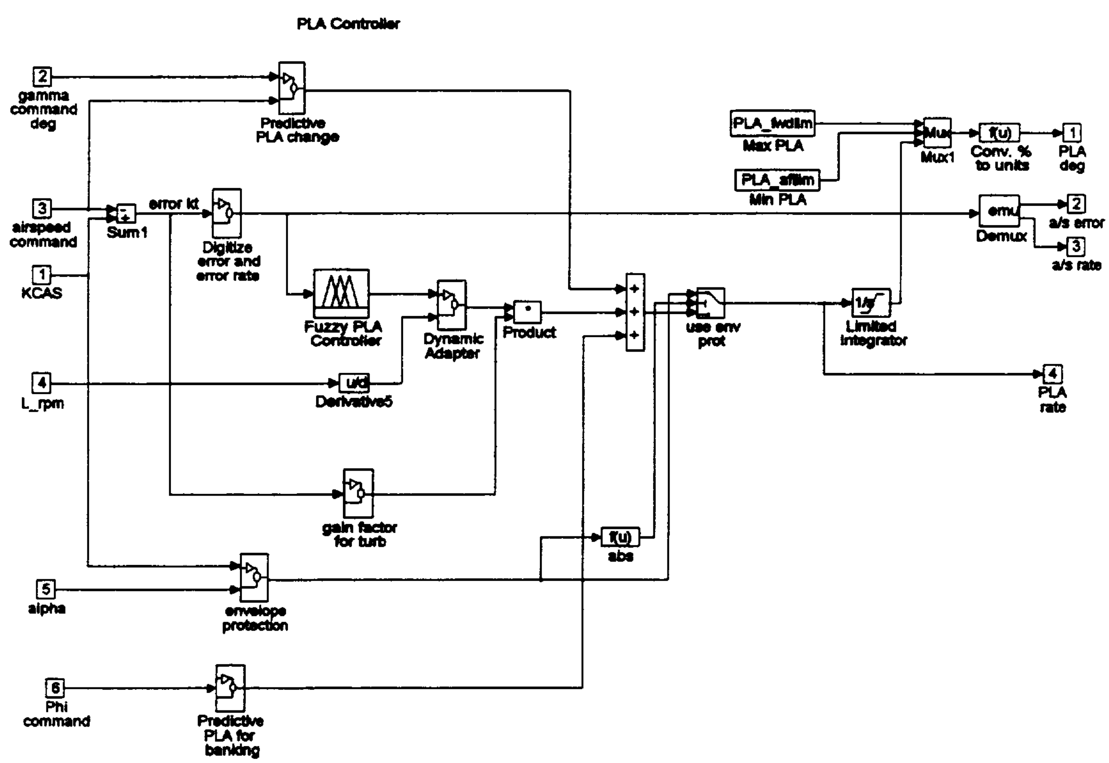


Figure 9. General overview of the final PLA controller including the predictive change in PLA as a function of changing bank angle.

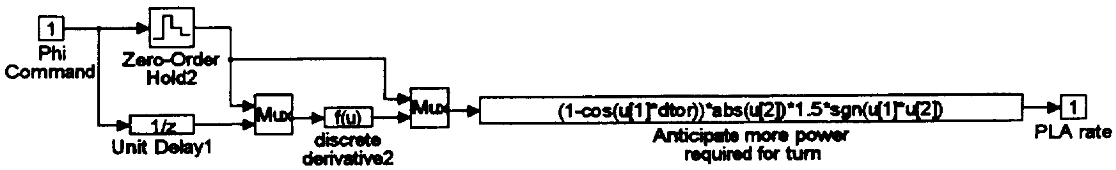


Figure 10. Predictive PLA change for bank angle block diagrams. u[1] is commanded bank angle and u[2] is commanded roll rate. See figure 10 for a plot of the predicted change in PLA function.

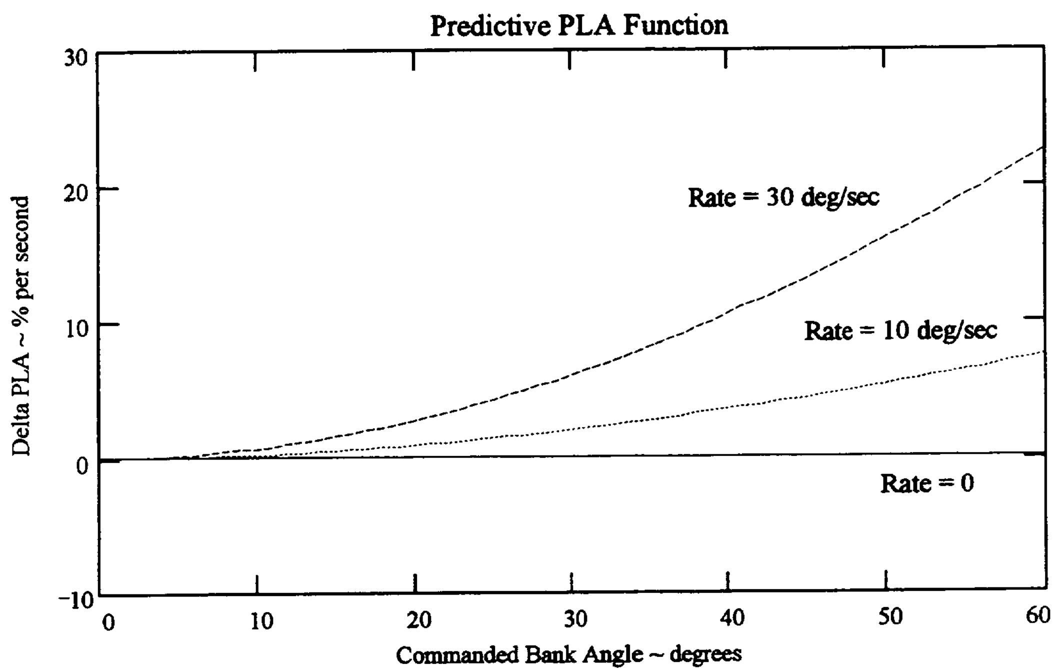


Figure 11. Predicted change in PLA as a function of commanded bank angle and roll rate.

4 REQUIRED CHANGES TO THE ELEVATOR CONTROLLER

The original elevator controller as described in reference 12 reserved an input to the fuzzy inference engine for a bank parameter. This input was replaced by a predictive elevator circuit similar to the predictive PLA circuit in the speed controller (see reference 12). This was done because the logitudinal predictive controller circuits worked well and was easier to impliment than modifying the fuzzy inference engine. Figures 12, 13 and 14 show how this function was implemented.

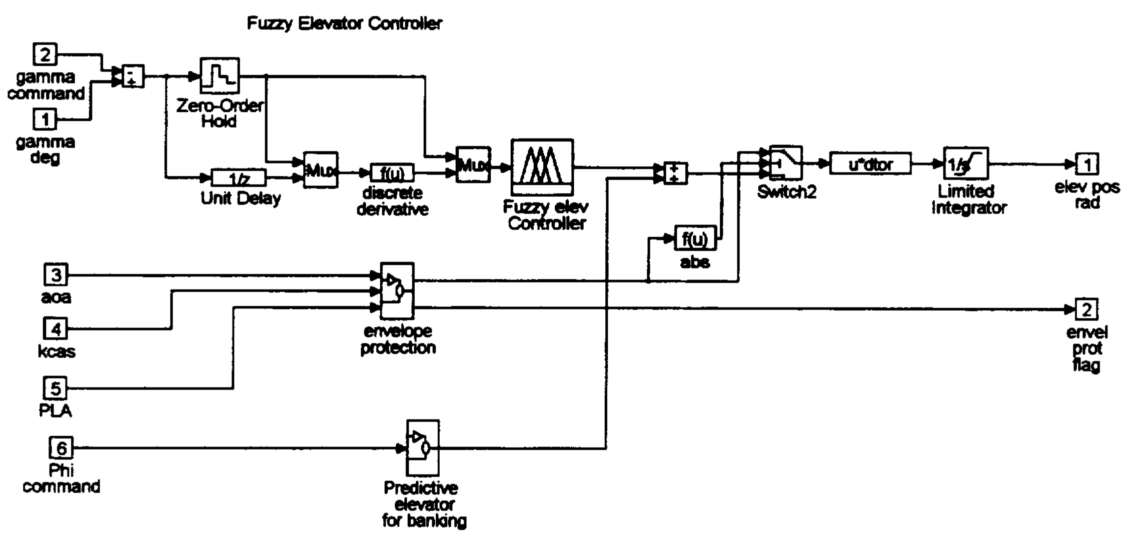


Figure 12. General overview of the final elevator controller including the predictive elevator for banking function block.

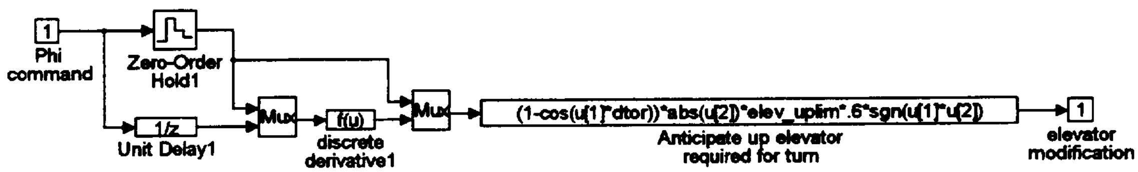


Figure 13. Predictive elevator change for bank angle block diagrams. u[1] is commanded bank angle and u[2] is commanded roll rate. See figure 14 for a plot of the predicted change in elevator rate function.

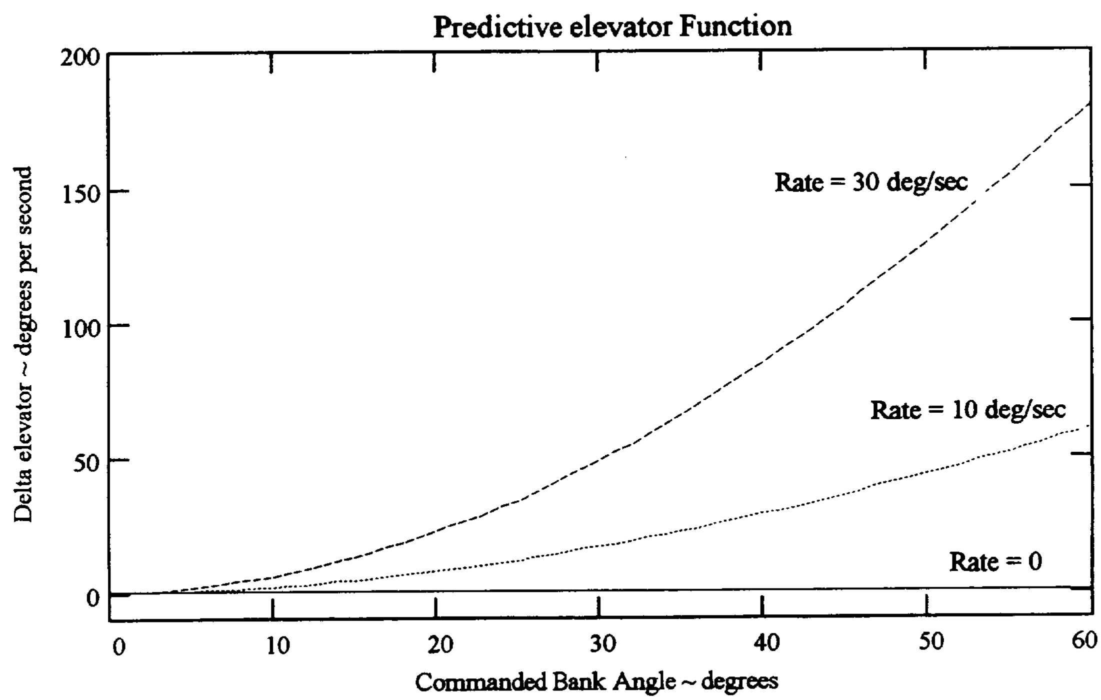


Figure 14. Predicted change in elevator as a function of commanded bank angle and roll rate.

5 RESULTS

The following maneuvers were chosen to demonstrate the characteristics of the controllers with both of the airplanes. Because of the differences in the normal flight envelopes between the two airplanes, identical maneuvers were not flown for both airplanes. Each manuever was chosen with a particular airplane to demonstate the controller/airplane characteristics in either a normal or envelope protection mode.

The following simulations were run for the jet airplane.

1) 150 knots at 12,000 feet with 30 degree bank right then 30 degree bank left while commanding a constant airspeed and level flight.

2) 150 knots at 12,000 feet with a 60 degree right bank while commanding constant airspeed and level flight. This bank angle and airspeed requires an angle of attack higher than the stall protection circuit allows.

3) 250 knots at 12,000 feet with a 60 degree bank right followed by a 60 degree bank left while commanding a constant airspeed and level flight.

4) 250 knots at 35,000 feet (Mach 0.74) with a 30 degree bank to the right then a 30 degree bank to the left while commanding a constant airspeed and level flight. This condition is just past the simulation's maximum level flight speed.

The following simulations were run for the piston airplane.

1) 130 knots at 1,000 feet with 60 degree bank right then 60 degree bank left while commanding a constant airspeed and level flight.

2) 130 knots at 1,000 feet while commanding 90 degrees right bank, constant airspeed and level flight. This forced the overbank protection to become active.

3) Starting at 130 knots and 1,000 feet commanding 45 degrees bank, an airspeed below stall and a climb angle that would allow rapid deceleration. This maneuver caused the stall protection circuit to activate continuously while a bank angle is commanded.

4) Starting at 130 knots and 1,000 feet commanding a bank angle of 45 degrees, an airspeed higher than the maximum allowed for this airplane and a flight path angle that would allow for rapid acceleration past maximum speed. This maneuver caused the overspeed protection circuit to activate twice while a continuous bank of 45 degrees was commanded.

5.1 Jet Simulation Results

Figures 15 and 16 show a time history of the jet simulation at 150 knots and 12,000 feet. In this simulation the airplane was given a command to bank 30 degrees right in 5 seconds. At 80 seconds the airplane was commanded to roll to 30 degrees left in 5 seconds. The elevator and throttle responded to keep the airspeed within 10 knots and altitude within 30 feet with the maximum excursion occurring during the initial 30 degree right bank. Note that the altitude excursion is measured from the start of the maneuver instead of from the initial altitude. This is because there is no altitude hold function in effect, only a vertical flight path angle command. Roll attitude followed the command very well and normal acceleration due to elevator inputs from the turn command were within the levels produced by the turbulence.

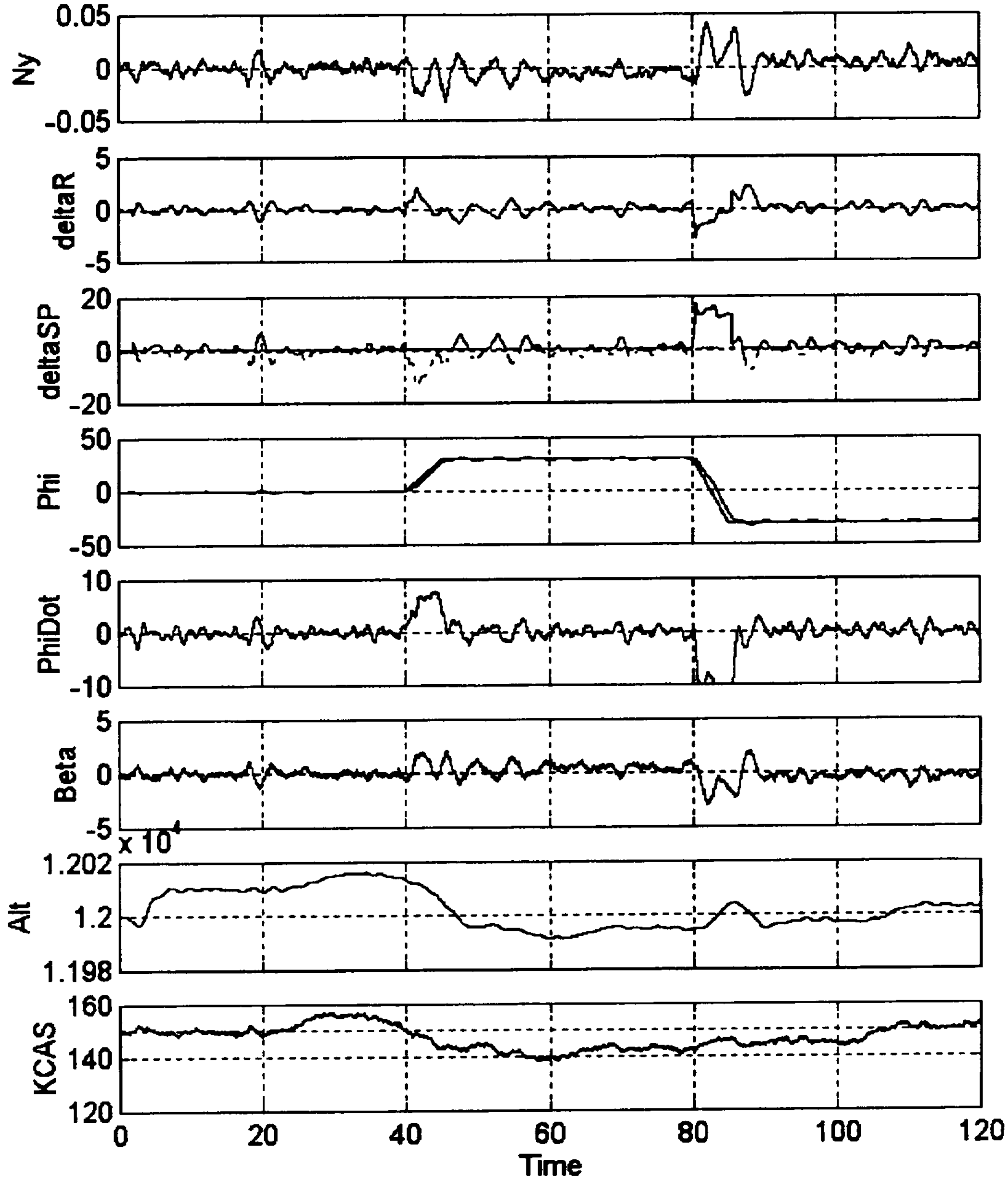


Figure 15. Lateral parameters for 30 degree banks left and right at low speed and low altitude for the jet.

See figure 31 (page 46) for legend.

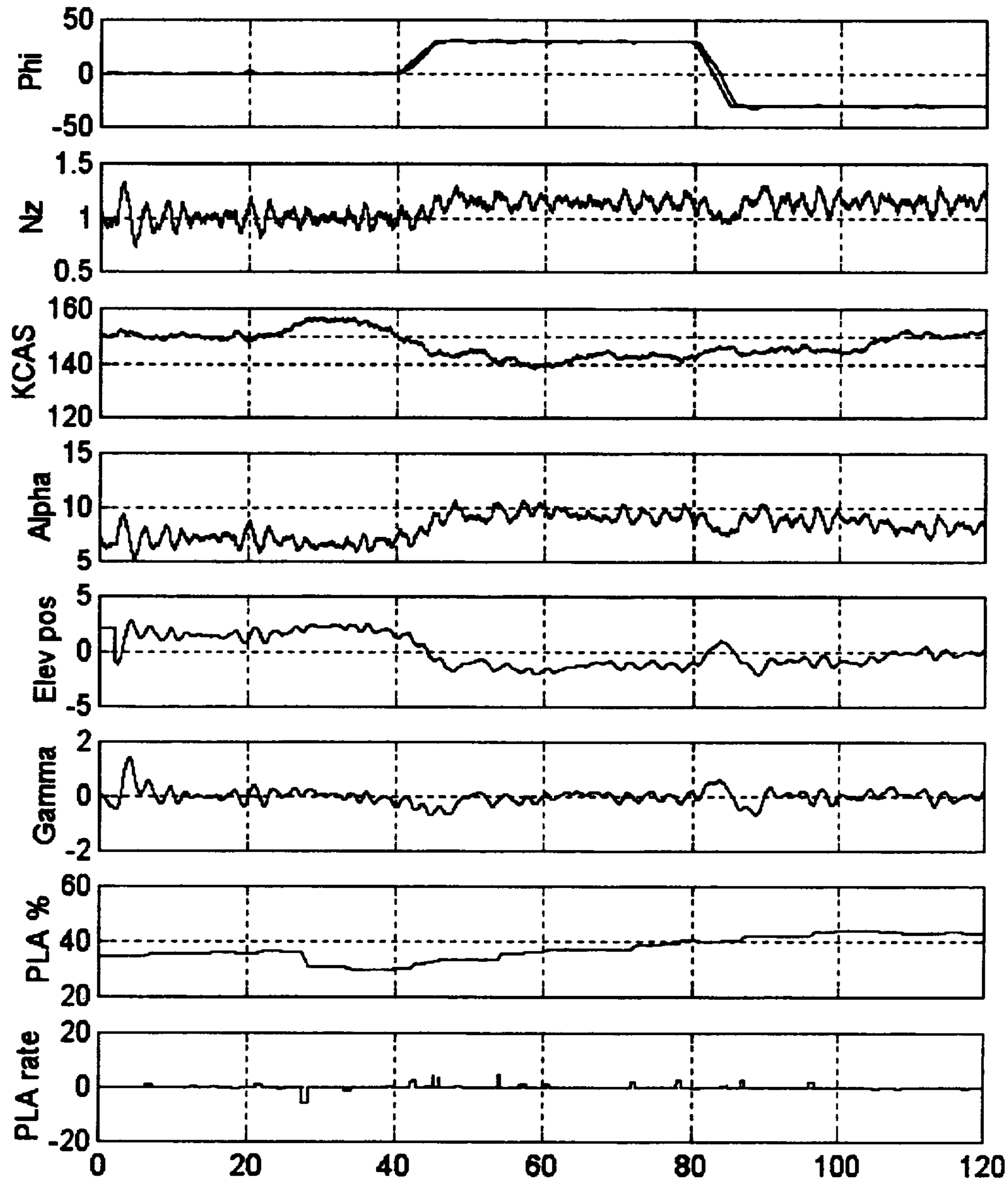


Figure 16. Longitudinal parameters for 30 degree banks left and right at low speed and low altitude for the jet.

See figure 31 (page 46) for legend.

Figures 17 and 18 show a time history of the jet simulation at 250 knots and 12,000 feet. In this simulation the airplane was given a command to bank 60 degrees right in 5 seconds. At 90 seconds the airplane was commanded to roll to 60 degrees left in 5 seconds. The elevator and throttle responded to keep the airspeed within 10 knots and altitude within 30 feet with the maximum excursion occurring during the initial 60 degree right bank similar to the response in the low speed case. Roll attitude followed the command very well and normal acceleration due to elevator inputs from the turn command were smooth. The higher bank angles for this high speed case show the predictive throttle inputs much more clearly than the low speed case. These inputs can be recognized by the curved ramp shape in the PLA rate trace (the normal error corrections are square pulses).

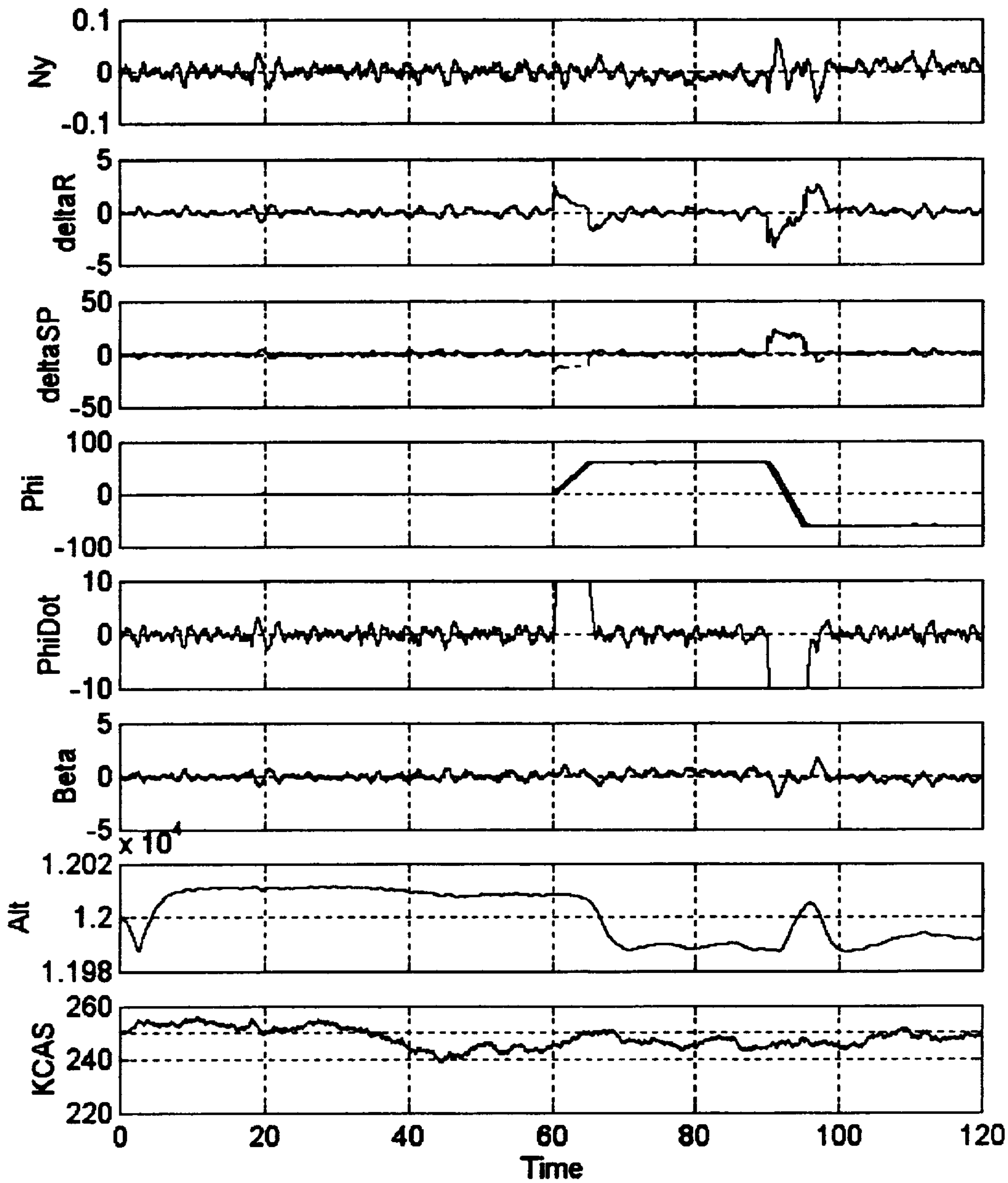


Figure 17. Lateral parameters for 60 degree banks left and right at high speed and low altitude for the jet.

See figure 31 (page 46) for legend.

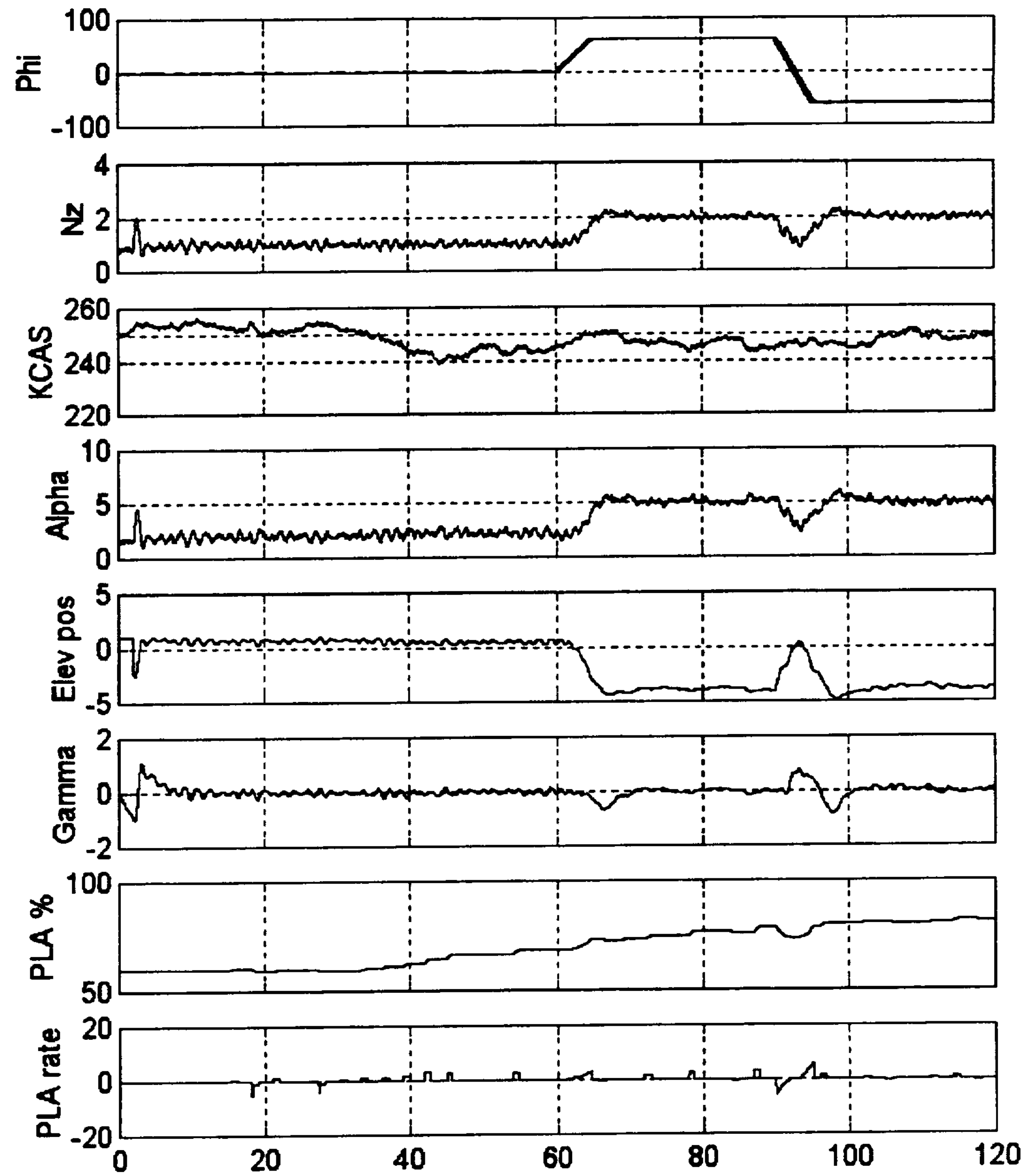


Figure 18. Longitudinal parameters for 60 degree banks left and right at high speed and low altitude for the jet.

See figure 31 (page 46) for legend.

Figures 19 and 20 show a time history of the jet simulation at 250 knots and 35,000 feet (Mach 0.74). In this simulation the airplane was given a command to bank 30 degrees right in 5 seconds. At 80 seconds the airplane was commanded to roll to 60 degrees left in 5 seconds. In this case, the flight condition (weight, temperature) was such that level flight required more thrust than was available from the particular engines that were used in the simulation. The elevator kept the altitude within 50 feet while the airspeed decayed from 250 knots to 200 knots. (Note that this is not an altitude hold system, but a flight path angle hold system. As such, the controller will not attempt to correct an altitude error since it does not know one exists.) The throttle controller kept the throttle at maximum throughout the maneuver. Roll attitude followed the command very well and normal acceleration due to elevator inputs from the turn command were smooth.

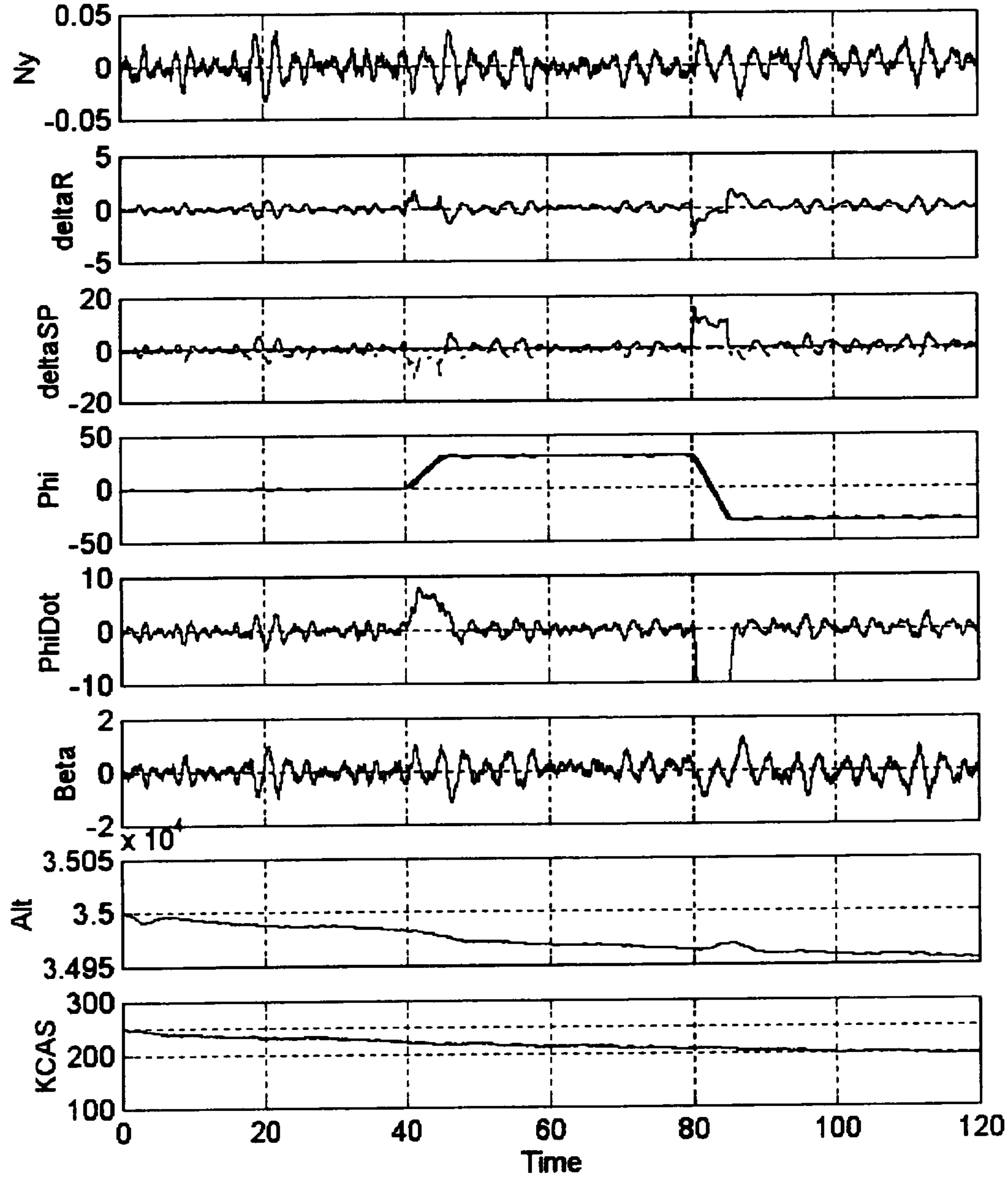


Figure 19. Lateral parameters for 30 degree banks left and right at high speed and high altitude for the jet.

See figure 31 (page 46) for legend.

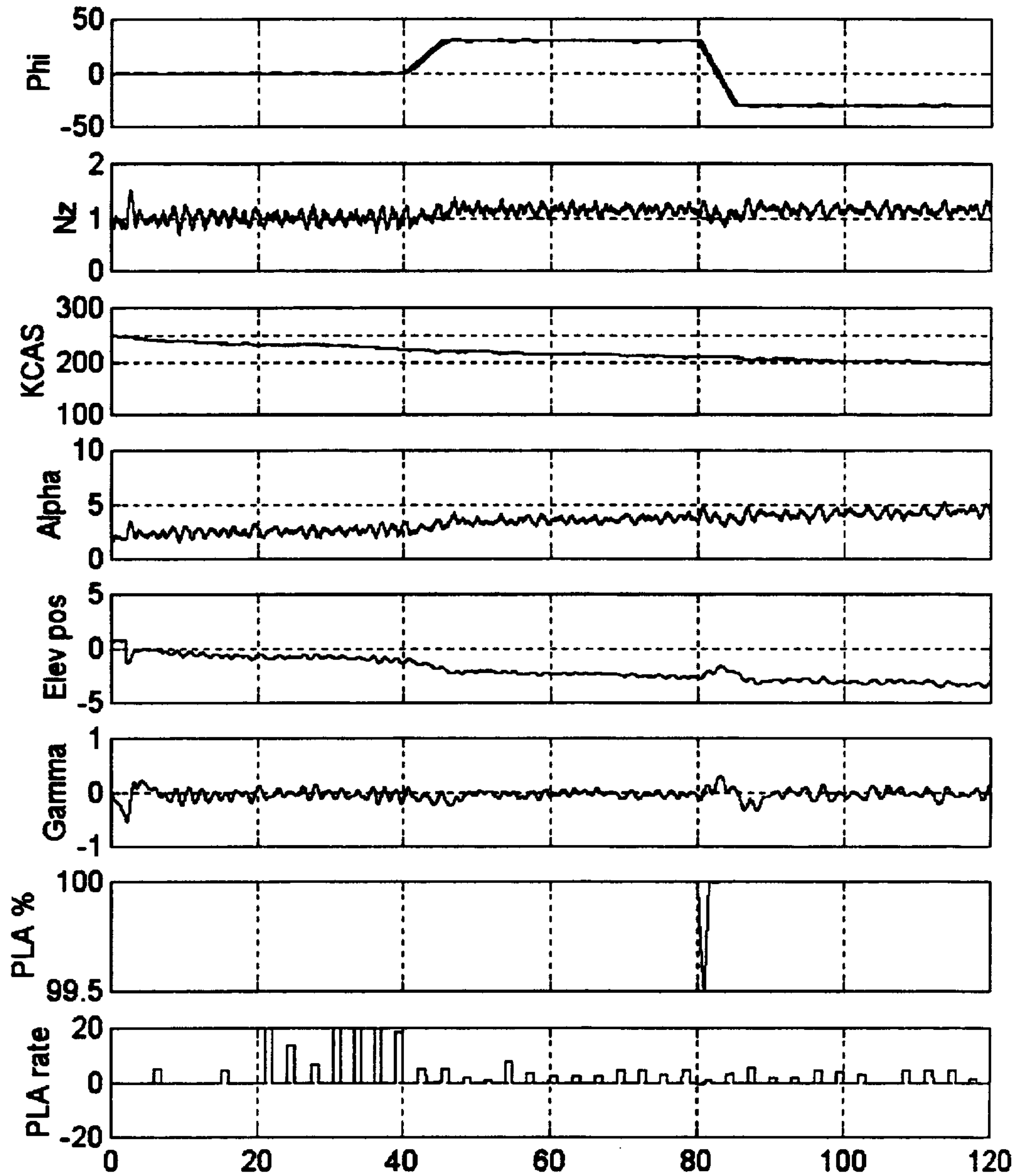


Figure 20. Longitudinal parameters for 30 degree banks left and right at high speed and high altitude for the jet.

See figure 31 (page 46) for legend.

Figures 21 and 22 show time history traces of the jet simulation at 12,000 feet and 150 knots with a bank angle command of 60 degrees. The load factor associated with level flight at these conditions requires an angle of attack (AOA) that is higher than that allowed by the stall protection circuit. When the angle of attack limit was reached all three controllers (speed, flight path and bank angle) went into stall recovery mode to immediately reduce AOA. As soon as aoa was once again below the limit, the controllers switched back to normal mode, and the cycle repeated. The thrust level remained high and the airplane accelerated and stabilized at a speed where the commanded bank angle could be maintained. This is because the stall protection circuit advances the throttle with no regard for engine response but the normal circuit does not retard the throttle until the engine speed is quasi-static,

The transitory oscillations were quite high. This was due to the on/off switching of the controllers into and out of the stall protection mode. If the stall protection feature had been incorporated into the fuzzy inference engine like the overbank feature was, then this transition would have been much smoother (see the overbank protection traces in figures 25 and 26).

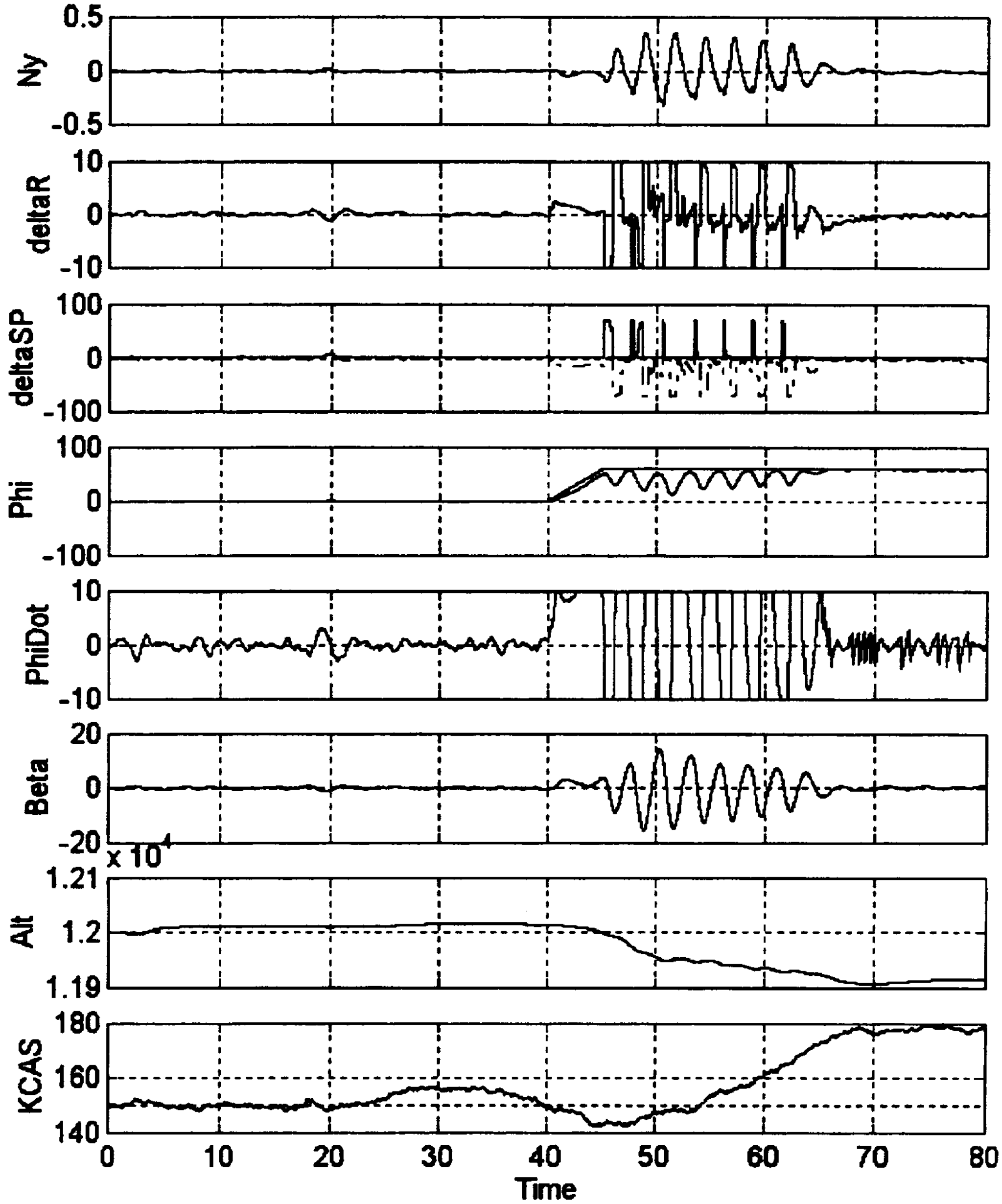


Figure 21. Lateral parameters for 60 degree bank with stall protection for the jet.

See figure 31 (page 46) for legend.

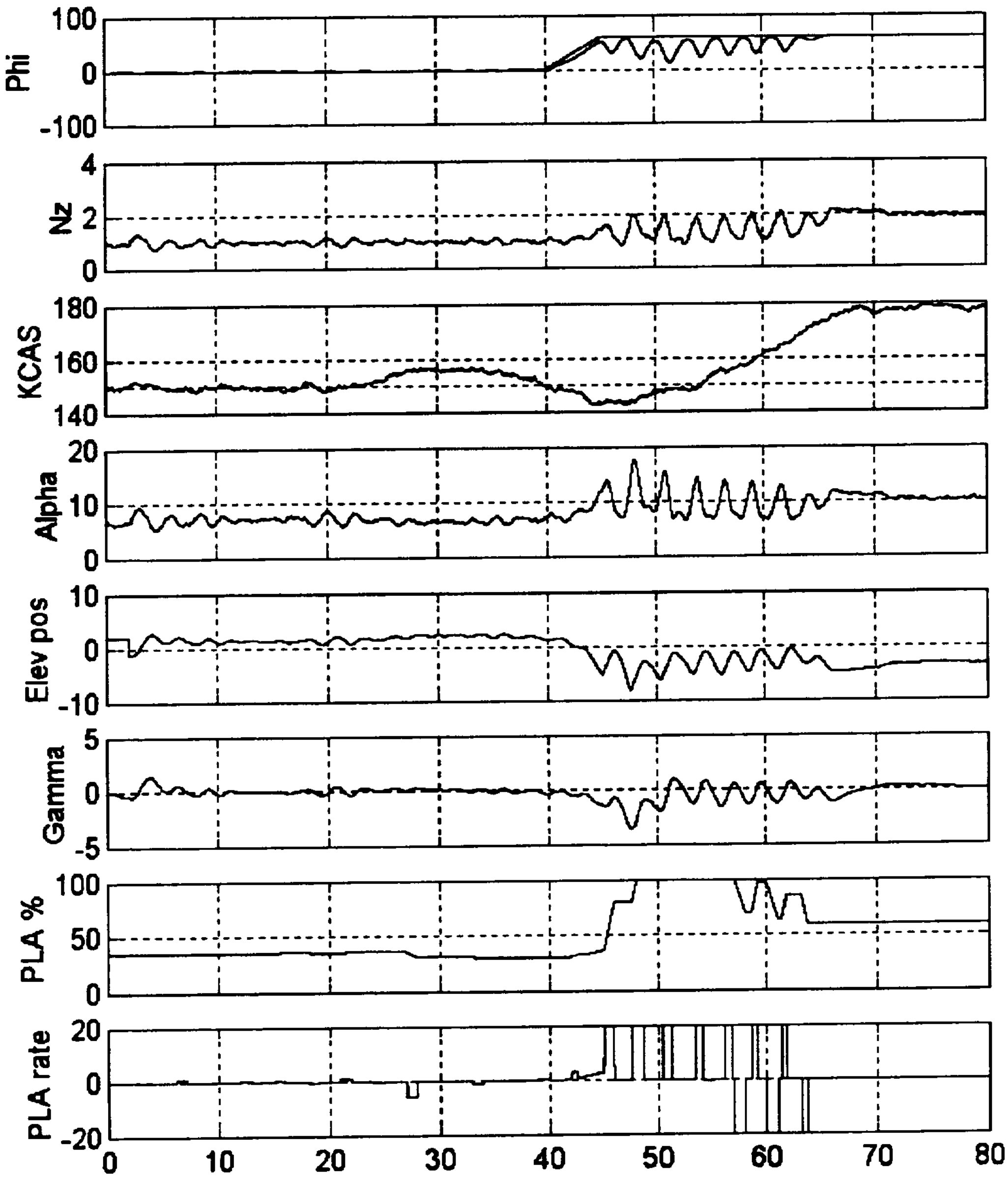


Figure 22. Longitudinal parameters for 60 degree bank with stall protection for the jet.

See figure 31 (page 46) for legend.

5.2 Piston Simulation Results

Figures 23 and 24 show a time history of the piston simulation at 130 knots and 1,000 feet. In this simulation the airplane was given a command to bank 60 degrees right in 5 seconds. At 80 seconds the airplane was commanded to roll to 60 degrees left in 5 seconds. The elevator and throttle responded to keep the airspeed within 10 knots and altitude within 20 feet with the maximum excursion occurring during the initial 60 degree right bank. Roll attitude followed the command very well and normal acceleration due to elevator inputs from the turn command were smooth. As with the 60 degree case for the jet simulation, the predictive throttle inputs are clearly evident. These inputs can be recognized by the curved ramp shape in the PLA rate trace (the normal error corrections are square pulses). Note that the predictive throttle and elevator circuits moved their respective controls to near the zero bank position and then moved them back as the airplane banked in the opposite direction, thus avoiding the ballooning that is common with this maneuver.

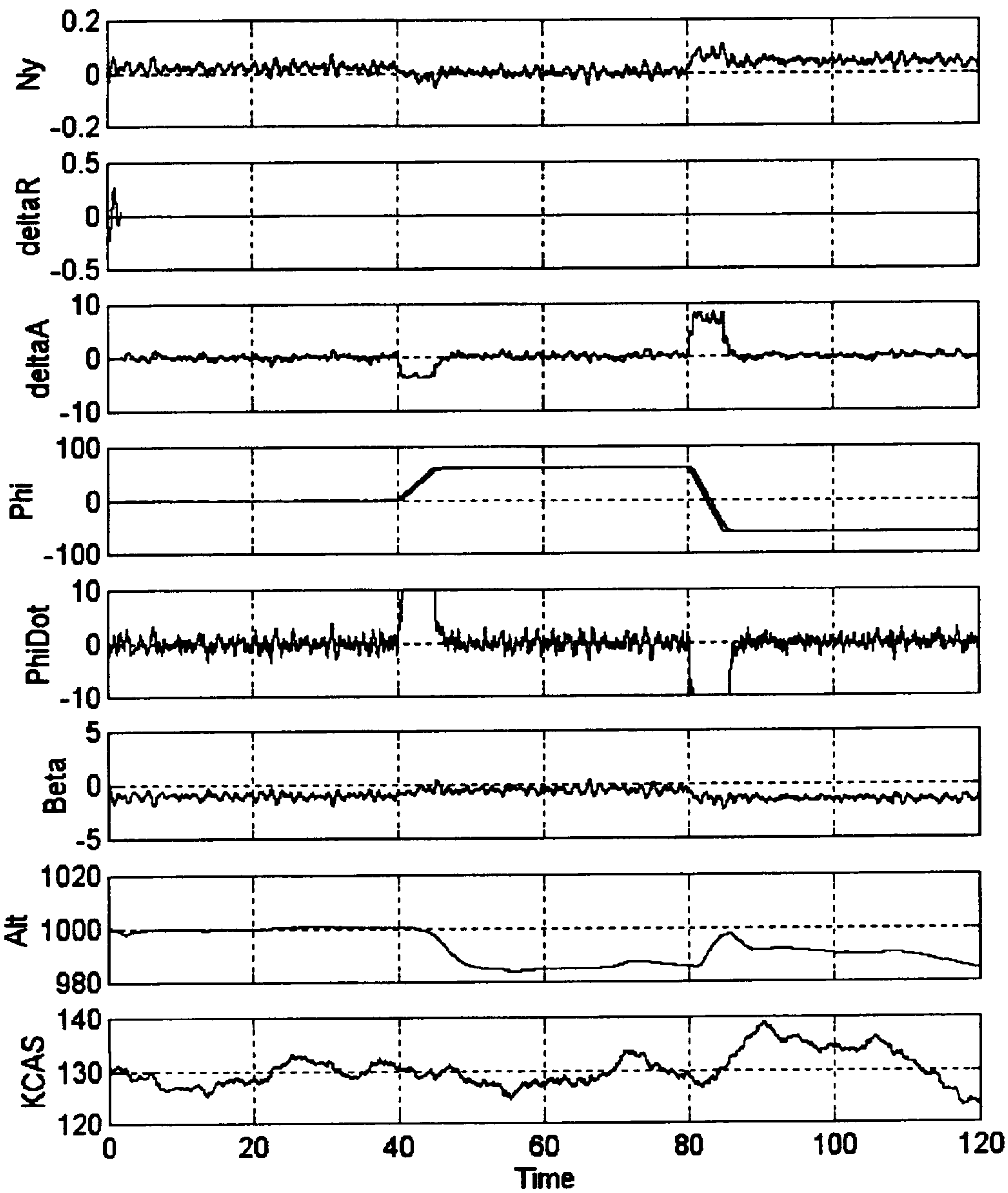


Figure 23. Lateral parameters for 60 degree banks left and right

for the piston simulation.

See figure 31 (page 46) for legend.

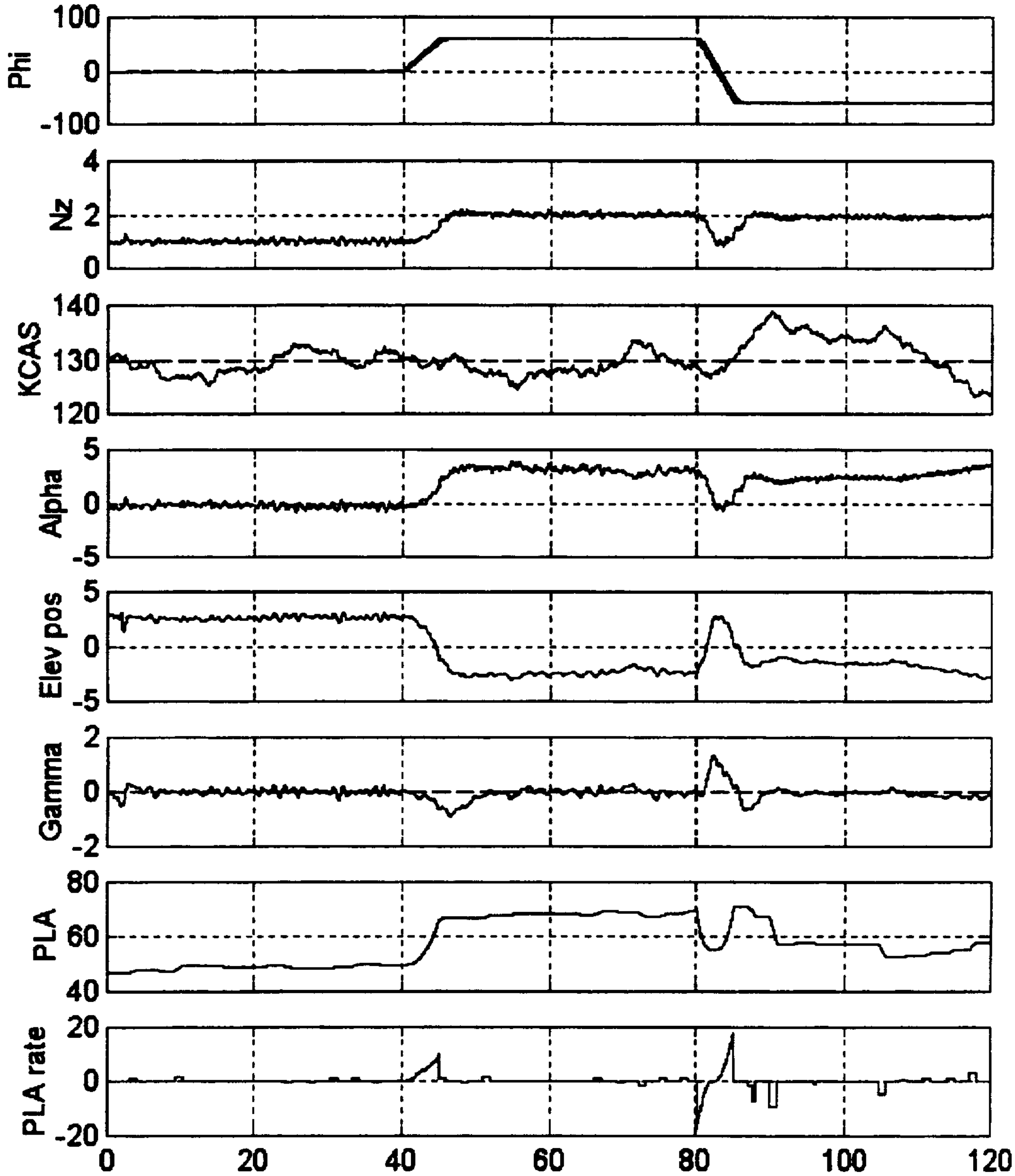


Figure 24. Longitudinal parameters for 60 degree banks left and right

for the piston simulation.

See figure 31 (page 46) for legend.

Figures 25 and 26 show how the overbank protection works. In order to activate this circuit, a bank angle of 90 degrees was commanded. It is expected that in a real installation the controller could not command a bank angle past about 60 degrees, and that the overbank protection would be triggered by turbulence or the wake of a larger airplane. However, for the purpose of examining the characteristics of this feature, the 90 degree bank command was used to trigger it.

The controller stopped the bank angle at 60 degrees and held it there smoothly (as compared to the oscillatory behavior of the other envelope protection circuits). The use of weighted rules in the fuzzy inference engine instead of switching modes is the reason why the response is much smoother. Note that the altitude and airspeed increase when the turn is commanded. The cause of this is that both the throttle and the elevator movement is exaggerated due to the 90 degree bank command. Both the elevator and throttle controllers use the commanded instead of actual bank angle for their predictive changes. Therefore the predictive circuits expect the airplane to go to 90 degrees when in fact the overbank feature only allows 60 degrees. The reason the commanded bank angle was chosen instead of the actual angle is because the command signal would have less noise and the actual angle should be close to the commanded angle anyway.

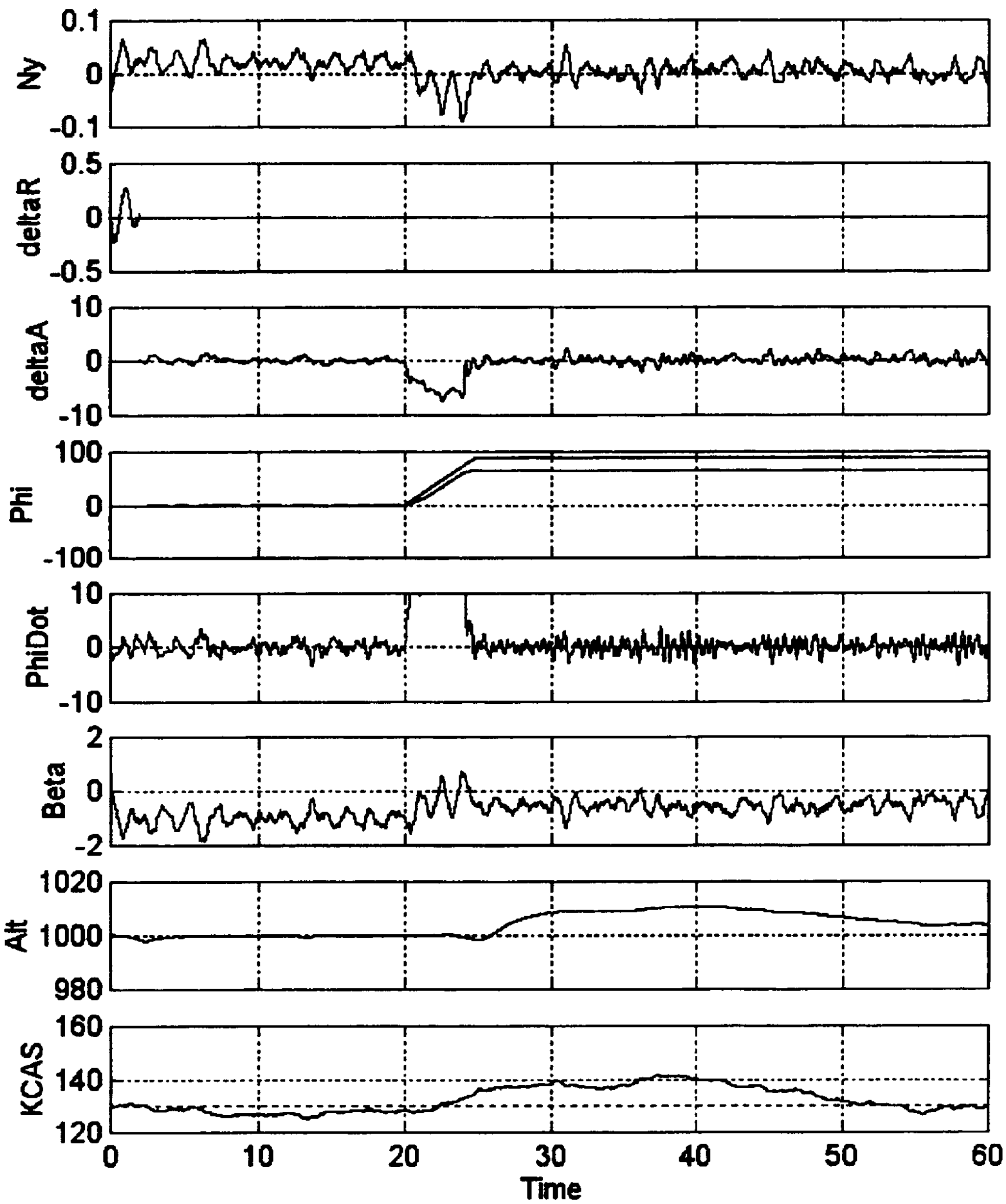


Figure 25. Lateral parameters for the overbank protection maneuver

with the piston simulation.

See figure 31 (page 46) for legend.

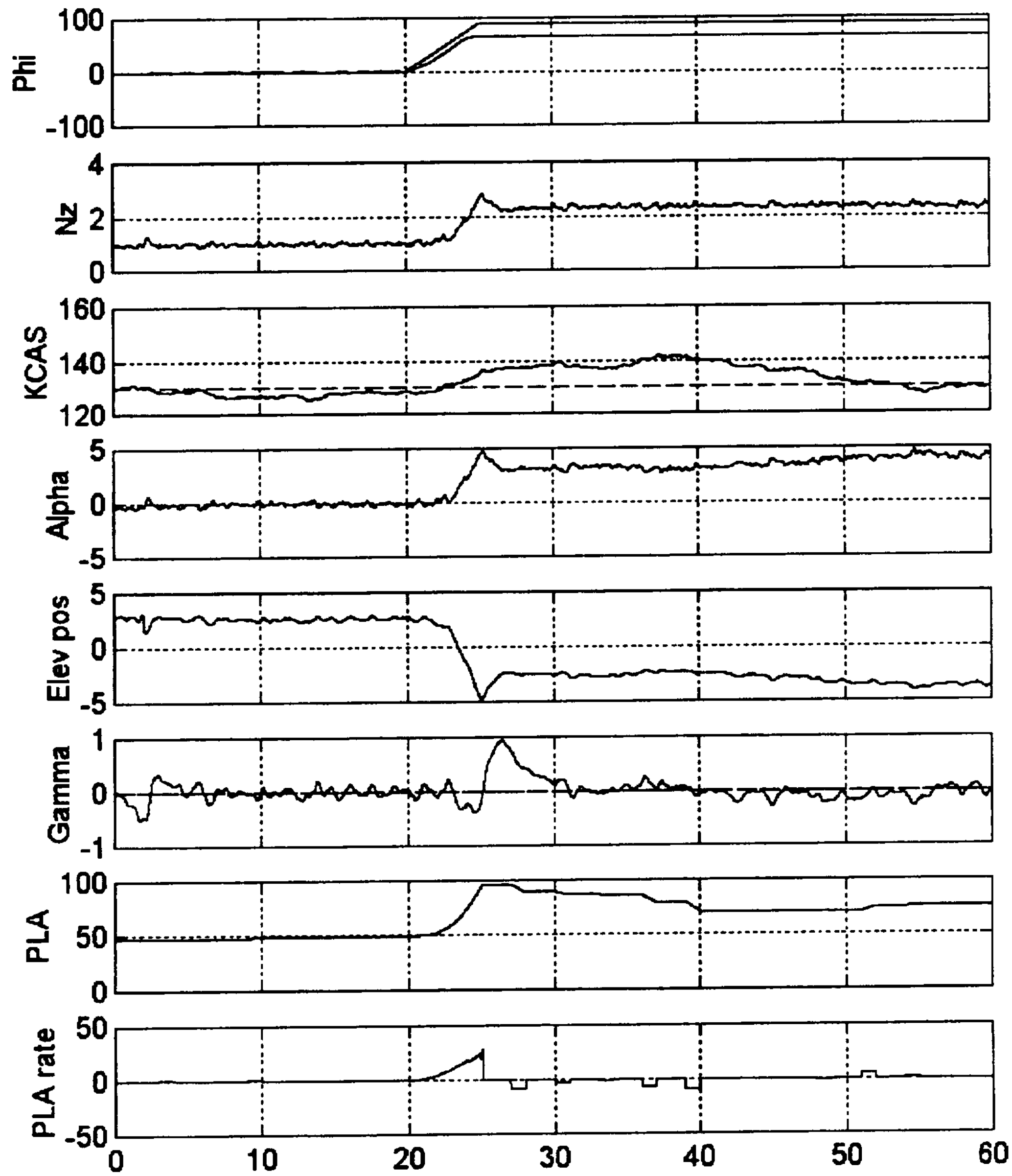


Figure 26. Longitudinal parameters for the overbank protection maneuver with the piston simulation.

See figure 31 (page 46) for legend.

Figures 27 and 28 show time history traces of the piston simulation starting at 1,000 feet and 130 knots. The airplane is then commanded to climb at a 15 degree angle and slow to 40 knots. This caused a rapid deceleration. As the airplane slowed through 100 knots a bank command of 45 degrees was given. The angle of attack required for these conditions is higher than the maximum allowed by the stall protection. When the angle of attack limit was reached all three controllers (speed, flight path and bank angle) went into stall recovery mode to immediately reduce aoa. As soon as aoa was once again below the limit, the controllers switched back to normal mode, and the cycle repeated. Because the stall protection circuit advances the throttle faster than the normal circuit retards it, the net result is a high power setting. The result is a steady flight speed at maximum power above the commanded speed while maintaining a climb angle close to the commanded climb angle. The bank angle is reduced with very active ailerons and unsteady (but banded) roll attitude.

The roll oscillations were high. This was due to the on/off switching of the controllers into and out of the stall protection mode. If the stall protection feature had been incorporated into the fuzzy inference engine like the overbank feature was, then this transition would have been much smoother (see the overbank protection traces in figures 25 and 26).

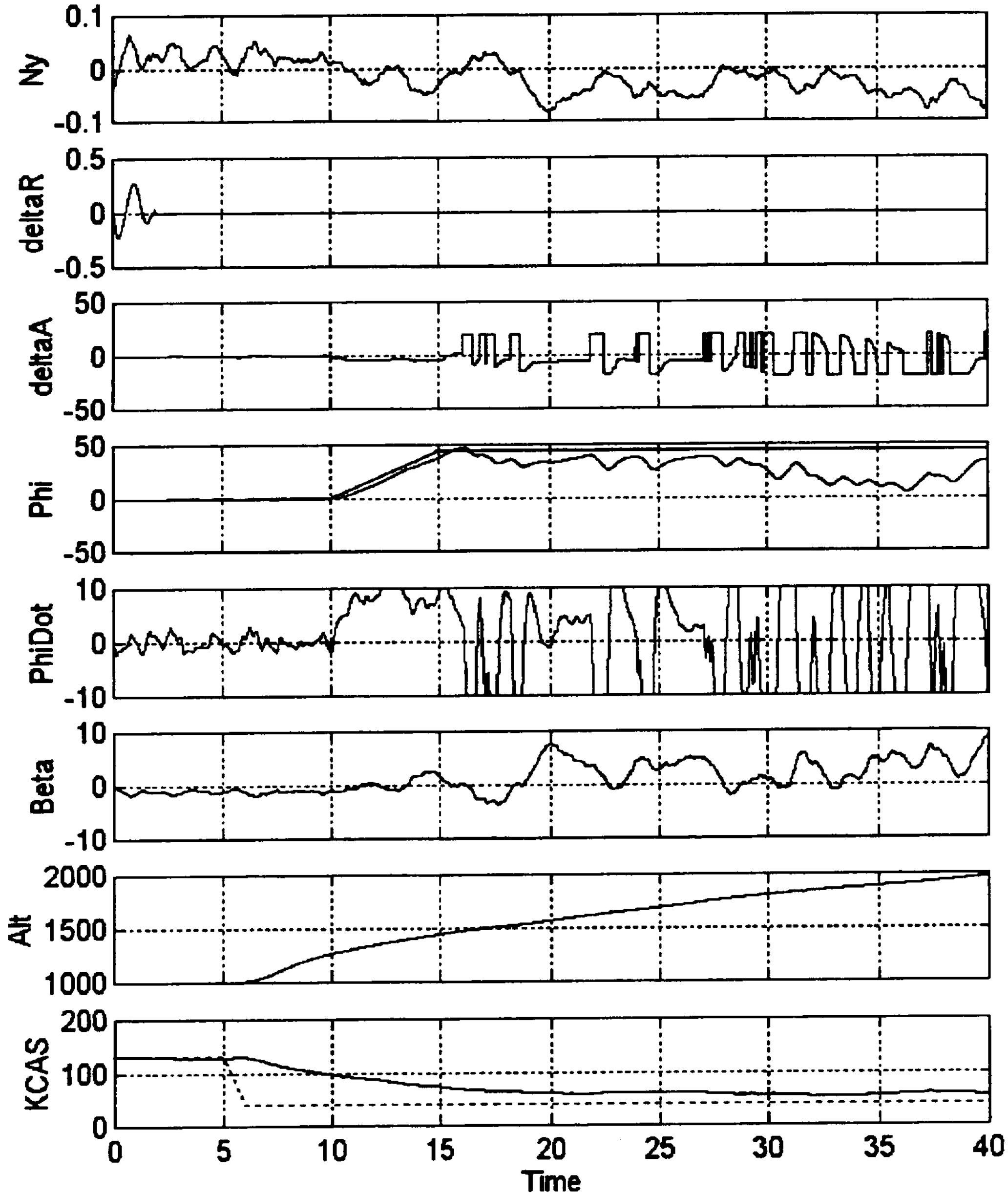


Figure 27. Lateral parameters for 45 degree bank with stall protection

for the piston simulation.

See figure 31 (page 46) for legend.

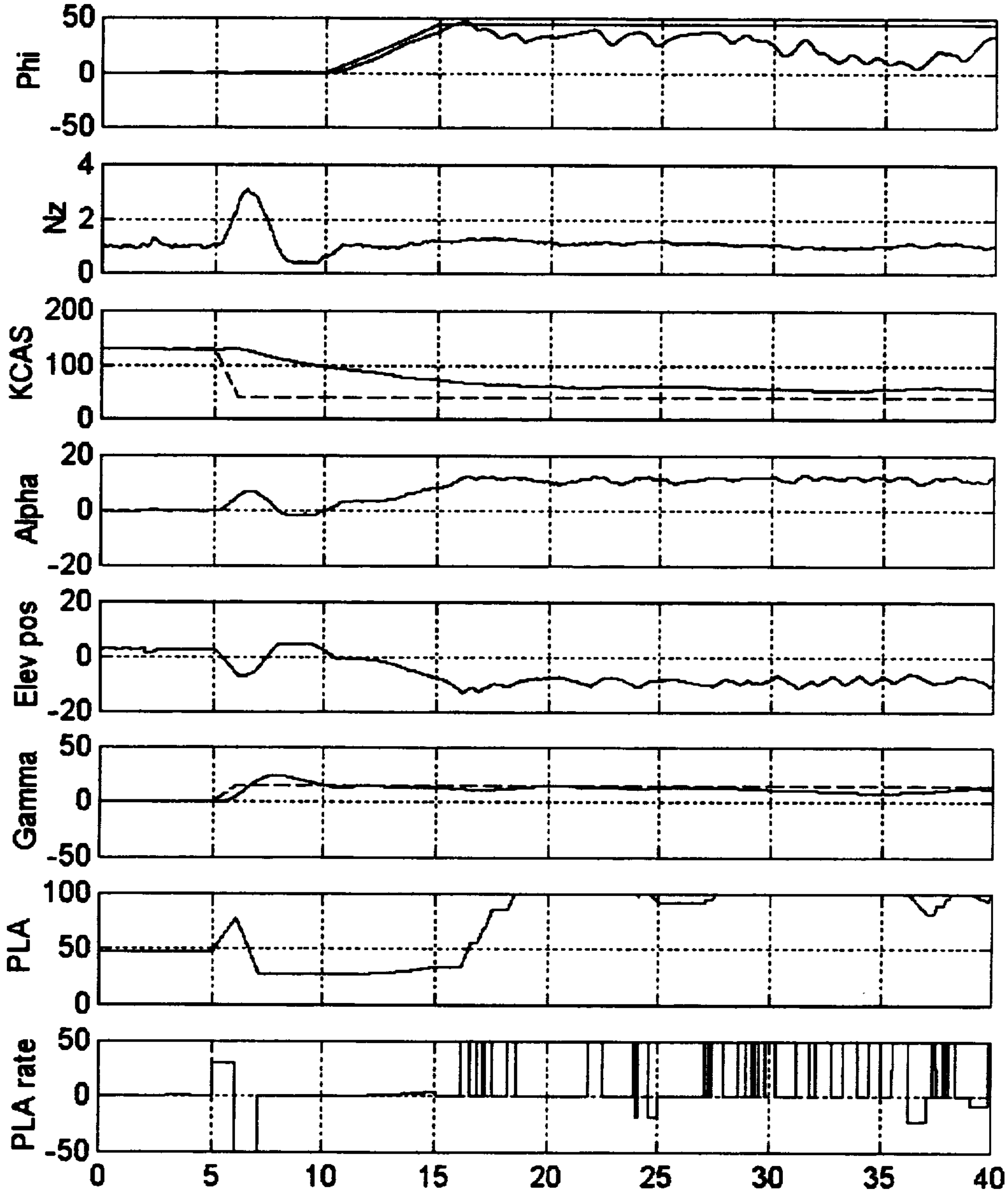


Figure 28. Longitudinal parameters for 45 degree bank with stall protection

for the piston simulation.

See figure 31 (page 46) for legend.

Figures 29 and 30 show the piston simulation starting at 130 knots and 1,000 feet. An airspeed command of 240 knots and a flight path command of 10 degrees down are given to cause the airplane to accelerate past the maximum allowed speed of 200 knots. As the airplane is accelerating through 150 knots, a bank angle of 45 degrees is commanded. The airplane follows this command smoothly until the airspeed exceeds 200 knots. At this time, the overspeed circuits on all three controllers activate and the throttle is reduced, the elevator moves trailing edge up and the bank command goes to zero. The airplane quickly rolls to about 10 degrees while the throttle is reduced to near idle. As the airplane slows to less than 200 knots the controllers switch back to following the commands that produced the overspeed, and a similar cycle repeats about 7 seconds later. In a real installation the command generator would not be allowed to command a speed above the maximum allowed.

In a real installation it is expected that the controller would not be allowed to command a speed above the maximum allowed minus a small pad. In this case, a higher speed was commanded to force the overspeed protection circuit to activate.

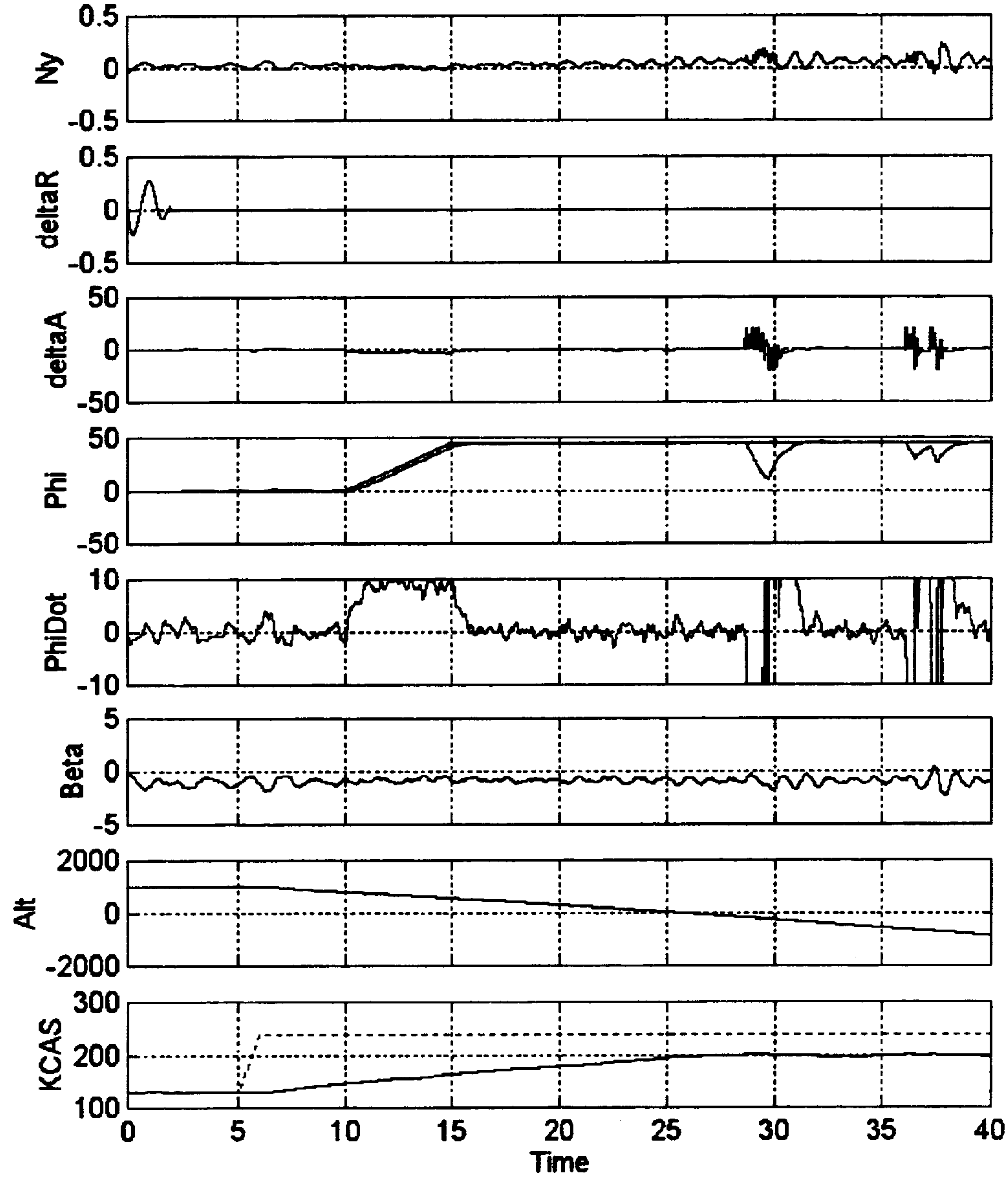


Figure 29. Lateral parameters for 45 degree bank with overspeed protection for the piston simulation.

See figure 31 (page 46) for legend.

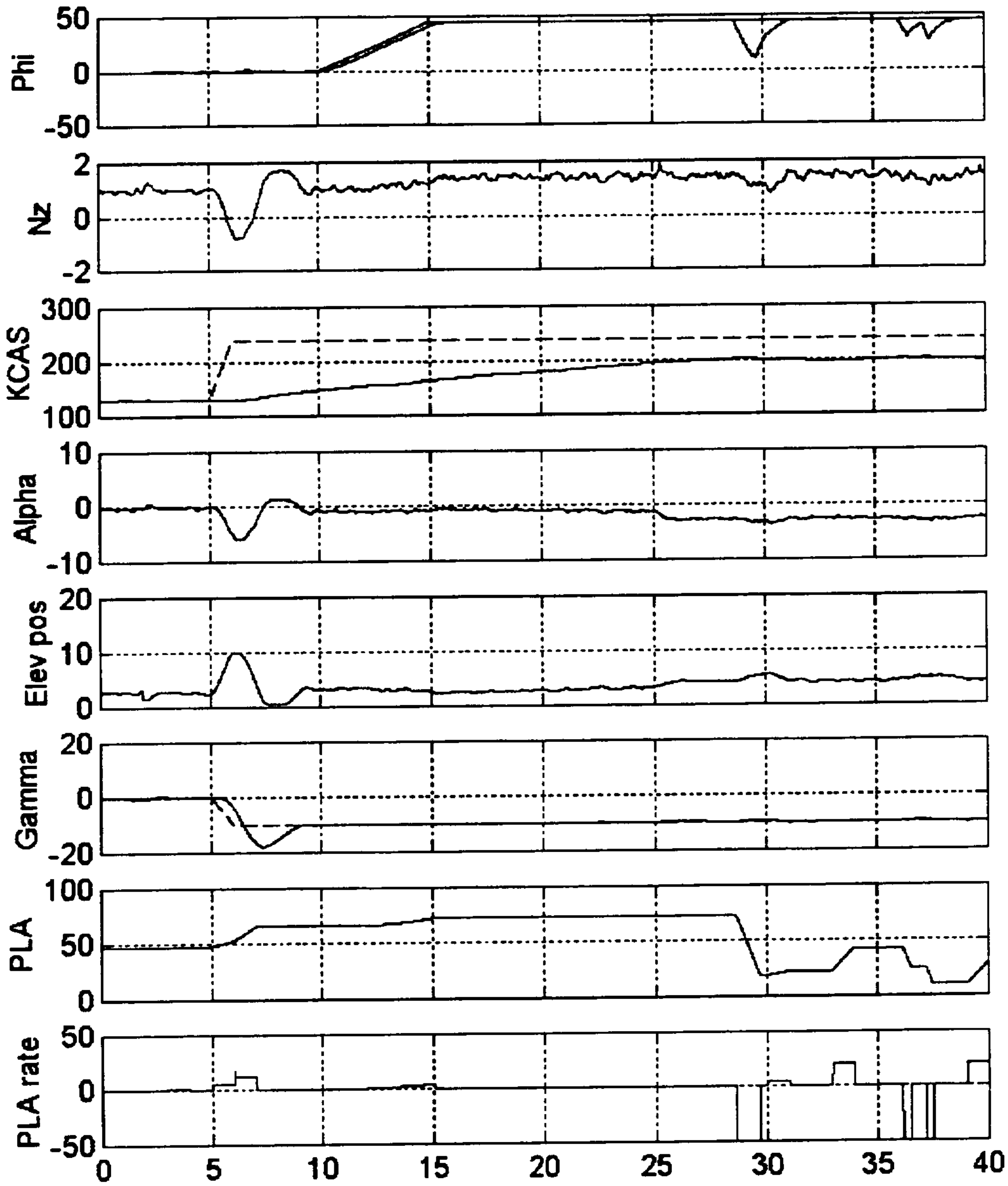


Figure 30. Longitudinal parameters for 45 degree bank with overspeed protection

for the piston simulation.

See figure 31 (page 46) for legend.

Plot Legend	
Ny	Lateral acceleration in gs
deltaR	Rudder position in degrees
deltaSP	Roll spoiler position in degrees (jet only)
deltaA	Aileron position in degrees (piston only)
Phi	Bank angle in degrees
PhiDot	Roll rate in degrees per second
Beta	Side slip angle in degrees
Alt	Altitude in feet
KCAS	Calibrated airspeed in knots
Nz	Normal acceleration in gs
Alpha	Angle of attack in degrees
Elev pos	Elevator position in degrees
Gamma	Flight path angle in degrees
PLA	Power lever angle (throttle) in percent
PLA rate	Power lever angle rate in percent per second

Figure 31. Legend for plot labels of figures 15 - 30

6 CONCLUSIONS

6.1 Observations

As was the case with the longitudinal controllers (reference 12), the fuzzy logic based lateral controller worked just as well with the piston simulation as with the jet simulation. The swept wing jet with spoilers for roll control needed a yaw damper to obtain satisfactory roll characteristics in the simulation just as in the real airplane.

The experience from designing the longitudinal controllers suggested that if the jet characteristics were acceptable, then the piston characteristics would be as well. This in fact turned out to be the case. The response to the overbank condition was much smoother than the responses to the other envelope excursions. This showed that incorporating the envelope protection into the fuzzy inference engine with weighted rules is feasible and provides better characteristics than automatic mode switching with external circuits.

6.2 Lessons Learned

The overbank protection was incorporated in the fuzzy rule set as a set of rules with a weighting of 10 times the other rules. This caused the controller to transition smoothly from normal operations to envelop protection operations. The other controllers used an expert system to monitor the edges of the envelope and if they were exceeded, immediately switch to a recovery control strategy. When the recovery control caused the airplane to reenter the normal operating envelope, the controllers immediately switch back to the normal fuzzy logic based command tracking mode. This caused the airplane to cycle in and out of the normal envelope instead of smoothly operating just at the edge (as was the case with the overbank protection).

This contrast leads to the conclusion that the stall and overspeed protection features would probably operate in a much smoother manner if they were incorporated into the fuzzy engine

7 RECOMMENDATIONS

This research shows that there is a high probability of making a fuzzy logic based set of generic control laws work in a wide variety of general aviation aircraft to produce a decoupled flight control scheme. The next step should be to incorporate the algorithms developed into a man-in-the-loop simulation or flight test vehicle. Even though there are several improvements that have been identified, these improvements could be incorporated into the algorithm as computer code is written for incorporation into the machine.

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13. ABSTRACT ***(Maximum 200 words)***

It has been hypothesized that a human pilot uses the same set of generic skills to control a wide variety of aircraft. If this is true, then it should be possible to construct an electronic controller which embodies this generic skill set such that it can successfully control different airplanes without being matched to a specific airplane.

In an attempt to create such a system, a fuzzy logic controller was devised to control aileron or roll spoiler position. This controller was used to control bank angle for both a piston powered single engine aileron equiped airplane simulation and a business jet simulation wich used spoilers for primary roll control. Overspeed, stall and overbank protection were incorporated in the form of expert systems supervisors and weighted fuzzy rules.

It was found that by using the artificial intelligence techniques of fuzzy logic and expert systems, a generic lateral controller could be successfully used on two general aviation aircraft types that have very different characteristics. These controllers worked for both airplanes over their entire flight envelopes. The controllers for both airplanes were identical except for airplane specific limits (maximum allowable airspeed, throttle lever travel, etc.).

This research validated the fact that the same fuzzy logic based controller can control two very different general aviation airplanes. It also developed the basic controller architecture and specific control parameters required for such a general controller.

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