1991

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Recommended Citation

Steinberg, Marc, "A fuzzy logic based aircraft carrier landing system " (1991). *Theses and Dissertations.* Paper 18.

AUTHOR:
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TITLE:A Fuzzy Logic Based Aircraft Carrier Landing System

DATE: January 1992

A FUZZY LOGIC BASED AIRCRAFT CARRIER LANDING SYSTEM

by

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A Thesis
Presented to the Graduate Committee
of Lehigh University
in Candidacy for the Degree of
Master of Science
in
Mechanical Engineering

Lehigh University

1991

CERTIFICATE OF APPROVAL

This thesis is accepted and approved
in partial fulfillment of the requirements
for the degree of
Master of Science
in
Mechanical Engineering

Dec. 7, 1991
date

Professor in Charge

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ABSTRACT

This thesis describes initial development and evaluation of an F/A-18 Fuzzy Logic Automatic Carrier Landing System(FACLS). The FACLS is designed so that at touchdown on the carrier, the aircraft has the proper position, sink rate, angular attitudes, and speed. Further, this is done with limited control authority, and under varying conditions of carrier motion, air turbulence, radar tracking noise, and ship air wake. The FACLS has eleven sensor inputs, three effector outputs, and approximately 400 fuzzy rules. The small number of rules is possible due to two factors. For one, instead of using a pure fuzzy logic controller, a classical control structure that contains five fuzzy-logic elements is used. The other factor that decreases the number of required rules is the use of variable membership functions. This use of fuzzy logic control is also different from many applications since fuzzy logic is not used only to model a set of human rules, but to combine the best features of human and automatic control approaches. This includes improving system acceptability by making it sensitive to pilot concerns that cannot be easily accommodated in conventional control systems. The FACLS was tested in simulation and compared with the current F/A-18 Carrier Landing System. Results indicate that the FACLS could yield significant improvements over the F/A-18 ACLS in its ability to make acceptable landings, particularly in severe weather conditions or with poor initial conditions.

1. INTRODUCTION

1.1 Background

Carrier landing is the most demanding task routinely done by Naval aircraft[1-9]. Medical studies have shown that carrier landing provides greater stress to pilots than actual combat in terms of respiration, pulse rate, and other physiological indicators[4]. This is because, unlike land-based operations, a carrier landing is essentially a precisely controlled crash on a small moving target with significant disturbances. Further, high performance jet aircraft do not perform well at the low approach speeds needed to make a successful arrested landing, and the landing must terminate, not only with the correct aircraft position, but also with acceptable pitch and roll attitudes, sink rate, and total speed. Due to the difficulty of this task, Automatic Carrier Landing Systems(ACLS) have been created[10-20]. Yet, ACLS's generally only track a specified glide slope and maintain correct angle of attack, angular attitudes, and sink rate. Unlike pilots, they cannot intelligently alter control strategies or plan ahead. Also, regardless of how well they work, ACLS's often cannot incorporate key pilot concerns. This decreases pilot confidence in the system, which is a major factor in determining the usefulness of any aircraft automatic control function. In addition, the Navy has long been interested in developing an ACLS that can safely be used under all weather conditions. Therefore, the goal of this thesis is to develop an improved carrier landing system that can take advantage of both heuristics developed by pilots, and control strategies developed by controls engineers, while remaining sensitive to key pilot concerns. One technology that has great potential for creating such a system is fuzzy logic[21-23].

Fuzzy logic has recently become the first machine intelligence technology to have wide-spread use in real-world control systems[24-35]. There are currently estimated to be several hundred systems that are either in use or have at least been field tested. Some of the most widely publicized examples include the subway system in Sendai, Japan[30], climate control systems[30], and cement kiln control[35]. There are many additional examples from the process control industry such as steel mill temperature regulation, water purification, furnace control, crane operation, and continuous casting plant control[29-30]. Fuzzy logic controllers are also beginning to be used in many consumer products such as camera autofocusing, camcorder stabilization systems, microwave ovens, washing machines, and automobile anti-lock brakes, transmissions, and fuel injectors[30,34-35]. One large company has recently stated plans to introduce 200 fuzzy logic products by 1995[34]. Another company has estimated it will gross 500 million dollars per year from fuzzy systems by 1995[34]. The reason for such expectations have been the benefits demonstrated thus far. Proven benefits of fuzzy logic controllers have included greatly improved performance, reduced power consumption, improved safety, reduced stresses on equipment, improved robustness, and much quicker development times. The fuzzy logic subway control system, for example, significantly improved the smoothness of acceleration and deceleration to the point that passengers supposedly cannot tell when the train stops and starts. This controller also has improved the accuracy of stopping points to a standard deviation of about 10 cm., reduced total power consumption by 10 percent, and decreased wear on subway componenents. Another successful example was the development of a camera auto-focus system. This system both improved the quality of focus and reduced average focusing time by twenty percent. A final fuzzy logic example is development of a fuzzy logic wind-tunnel controller[33]. The conventional controller designed for this task took close to two months to develop and required creation of a detailed process model. A comparable fuzzy logic controller, however, was developed in three days without the need for a process model.

Despite this excellent outlook, many of the successful applications of fuzzy logic have been for problems much easier than carrier landing. Nonetheless, recent laboratory work has begun to show the benefits of fuzzy logic based control for more difficult problems. Two examples of this stabilizing a three stage inverted pendulum on a cart[36], and parallel parking an automobile[32]. Both these problems had otherwise been unsolvable for conventional control theory or artificial intelligence methods. Some noteworthy laboratory demonstrations from the aerospace industry have included simulations of space shuttle trajectory control[37-40], spacecraft tether control[40], unmanned vehicle obstacle avoidance[40], and aircraft roll control[41]. Many of these simulations also found benefits such as quick development times, improved performance, and reduced energy consumption. The space shuttle trajectory controller, for example, has shown fuel savings of 20-70 percent in all attitude hold, rate hold, and maneuver cases as compared with the space shuttle automated attitude controller[40]. The spacecraft tether controller operated more smoothly than a conventional controller, and was able to reduce length error by one third to one half in preliminary testing.

One reason that fuzzy logic controllers have produced these benefits is that they can easily embed human if-then type rules into a mathematically based controller. For example, a representative fuzzy logic rule is *if an error is near zero and the rate of error increase is large, then move an effector a medium amount.* Yet, a fuzzy rule is a complex numerical mapping from the input space to the output space and functionally much different from a similarly stated classical logic rule. Fuzzy logic control is not, as its truly awful name seems to imply, some type of illogical or poorly considered reasoning. Instead, it is based on the idea that in real-world problems, it may be difficult to force everything to fit in exact categories. For example, in an expert system using classical logic, if an input is one micron larger than the definition of small, the system assumes the input is not small. Then all the rules relating to small inputs are completely irrelevant and all the rules for not small inputs perfectly apply. In contrast, a fuzzy system allows the possibility that rules for both categories might apply to some degree. Thus, instead of requiring a specific rule for each possible situation, a fuzzy controller can look at all potentially relevant principles of operation and determine an exact response based on some weighting of these principles. Further, since fuzzy logic is numerically based and not symbolically based, a great deal of mathematics can be brought to bear on a fuzzy logic controller. This includes analytical ways of determining stability and robustness[42-43].

Another key reason for fuzzy logic control's success is that it is a computationally efficient and somewhat transparent means for implementing complex non-linear control laws. Thus, it has allowed the creation of sophisticated non-linear control laws with less effort than is required for conventional non-linear control techniques like gain scheduling. Further, these control laws can then be implemented with reasonable computational overhead via the use of specialized fuzzy logic chips. This is possible because in a fuzzy logic controller, rules are in parallel and can be evaluated concurrently instead of in time-consuming tree searches. For example, currently, there are boards that can be inserted in a standard 286-based PC that can calculate as many as 30,000 fuzzy rules per second[44-46]. Further, these boards can be placed in parallel, allowing calculation of over a million fuzzy rules per second on a low-end computational platform like a PC.

1.2 Approach

The use of fuzzy logic control in this thesis has some differences from many current applications. The major difference concerns the nature of the rule base. Often the reason for developing a fuzzy logic controller is that there are human operators who can perform a task, but no easy way of creating an automatic control system. This typically occurs due to the lack of an accurate process model or the need for a complex non-linear control strategy. In contrast, for carrier landing, adequate process models are always developed and both human pilots and automatic systems can perform carrier landings acceptably. Just duplicating pilot technique would not yield significant improvements, and would likely decrease the capability of the system. Some pilot techniques, for example, are used to compensate for human weaknesses. Other pilot techniques rely on strictly human capabilities, like vision cues to which automatic systems do not have access(at least not yet). Also, pilots are given more control authority than automatic systems, and therefore can initiate maneuvers that automatic systems would not be allowed to perform for safety reasons.

Another significant difference between the FACLS and many fuzzy logic controllers, is that a pure fuzzy logic controller is not used. Instead, the system is organized much like a classical controller, with five key blocks being fuzzy rule bases. Four are standard fuzzy logic controllers, and the fifth also affects the gains in the classical control elements. This allows a significant reduction in the number of rules required and provided comparable performance to a pure fuzzy logic controller with a much larger rule base. Another difference between the FACLS and most fuzzy controllers is that fuzzy logic membership functions are not constant, but vary as a function of range to carrier. This significantly decreases the number of membership functions and rules required.

1.3 Thesis Overview

This thesis is organized in the following manner.

Section 2 provides a brief functional description of fuzzy logic controllers.

Section 3 provides a detailed overview of the carrier landing problem, piloting technique for carrier approach, and current automatic carrier landing systems.

Section 4 briefly describes the F/A-18 aircraft and the particular simulation used in this thesis.

Section 5 describes the Fuzzy Logic Carrier Landing System, and provides details of the development process and insight into why particular design decisions were made.

Section 6 describes the fuzzy logic controller's five rule bases in depth.

Section 7 presents the results of simulation of the FACLS and compares it with the current F/A-18 ACLS, which is the most advanced ACLS in operation in the fleet.

Finally, Section 8 presents the conclusions of this study.

2. FUZZY LOGIC CONTROL OVERVIEW

As briefly mentioned in the introduction, fuzzy logic is based on the idea that real-world problems are often difficult to put into classical logic expressions. In classical logic, for example, categories might be divided as shown in Fig. 1., where anything less than 5 is small, and anything greater than 5 is large. Fuzzy logic might break up the same categories as shown in Fig. 2, where instead of being exactly small or large, an input can belong to small or large with a degree of membership on the real line between 0 and 1. An input of 4, for example, would be small with a degree of 0.6 and large with a degree of 0.4. The curves in Fig. 2 are called membership functions. Triangles and trapezoids are often used since they are computationally simple, and they approximate mathematically tractable Gaussian curves. To extend classical logic operators to degrees of membership other than 0 or 1, the AND operator is usually taken as the minimum of the values and the OR operator is taken as the maximum. Note that this is exactly equal to classical logic if the only allowable input values are 0 and 1.

Creating controllers with fuzzy logic rules is typically done as shown in Fig. 3. There is an initial fan out layer that sends the inputs to each rule. Each rule can then be evaluated concurrently using specialized chips. Finally, all rules that are activated to some degree are combined in a final exact output with a summation process called defuzzification(another truly awful name). There are a number of ways of performing these operations. A look at one way this summation process can be done for two activated rules is shown in Fig. 4. The first step in this process is to fuzzify the inputs by checking the inputs degree of membership in all relevant categories. In this case, position is small with degree 0.25 and zero with degree 0.0. Velocity, on the other hand, is large with degree 0.6 and small with degree 0.4. Rule 1 states that if position is small and velocity is large then actuator position should be large. The total activation of Rule 1 is then 0.25 since under fuzzy logic

$$0.25 \; AND \; 0.6 = MIN(0.25, 0.6) = 0.25 \tag{1}$$

Similarly, the degree of activation of Rule 2 is 0.6 since

$$0.6 \; OR \; 0.0 \; = MAX(0.6, 0.0) = 0.6 \tag{2}$$

Note that this step is just a mapping between unit hyper-cubes. On the right of Fig. 4 are the membership functions of the consequents of each rule. These membership functions are multiplied by .25 and .4 respectively since this is the degree of activation of each rule. This yields the smaller triangles as the fuzzy outputs of each rule. The final step, defuzzification, is used to return an exact output from the controller. The way this is done in Fig. 4 is by taking the centroid of the two modified consequent membership functions using

$$y = \frac{\Sigma_{i=1}^{2} A_i B_i}{\Sigma_{i=1}^{2} A_i} \tag{3}$$

where y is the actuator command and A_i and B_i are the area and centroid, respectively for each modified consequent membership function.

In some ways this parallel structure is much like a traditional three layer neural network, with a fan out layer, the fuzzy rules forming a layer of non-linearities, and a final summation layer. Thus, neural network techniques like backward error propagation learning or adaptive vector quantization for initial placement of rules can be brought to bear. However, learning has some advantages over conventional three layer neural networks since the rules are only active in one area of the input space. This means that when learning in one area of the space, significant changes probably will not be made in other areas of the input space. Also, where conventional neural network structures are often very difficult to understand and validate, fuzzy logic systems are more transparent due to their representation in English rules.

3. CARRIER LANDING OVERVIEW

As mentioned in the introduction, a carrier landing is essentially a precisely controlled crash on a small moving target. For the landing to be successful, the aircraft must be high enough to clear the carrier ramp, but low enough to engage the number 4 wire as shown in Fig. 5. Typically, the ship's Landing Signal Officer(LSO) will insist on much tighter bounds than this, including clearing the carrier ramp by at least seven feet. In addition, the landing must occur with wings level, the proper horizontal position, and an acceptable sink rate and total velocity to prevent damage from a hard landing. Achieving these goals is difficult since high performance jet aircraft have unforgiving dynamics at low approach speeds and the landing must be performed in the presence of carrier motion, the carrier air wake, normal air turbulence, and radar tracking noise. Further, the final stage of the approach takes place in about 30 seconds, with the aircraft moving at over 200 ft./sec. Thus, any corrections must be made in a very limited amount of time. The time to make corrections is further constrained by an allowable envelope the aircraft must remain in to avoid a wave-off by the ship's LSO. Thus, successful carrier landing requires aggressive closed loop control that makes optimal use of all available control power.

3.1 Pilot Techniques for Carrier Landing

A complete carrier landing is composed of several legs as shown in Fig. 6[10]. This thesis only examines the final and most difficult leg of the approach when the pilot or ACLS begins tracking glideslope. It is assumed that the aircraft has been trimmed close to the proper approach speed and sink rate with wings level. Pilot techniques for this final stage of the approach are not well defined in available Naval literature. There is a very strong Naval operational doctrine that pilots are required to follow[7]. Still, within this doctrine there is room for individual techniques. These techniques are difficult to discern from conversations with pilots and landing signal officers for several reasons. First, unlike the traditional control system operator, pilots are an integral part of the closed loop system with a significant effect on the dynamics of the system. Thus, pilot responses are not made following a clear and well established set of quantifiable rules, such as may be done by the operators of simpler processes. The second reason for the difficulty of determining pilot techniques is that carrier landing is a two-man-in-the-loop operation between a pilot and a ship-board Landing Signal Officer(LSO). Besides calling wave-offs, the LSO provides considerable help to the pilot in determining how to deal with carrier motion. The LSO also is excellent at spotting trends that may lead to error conditions and providing guidance to help the pilot remain within tight bounds. The final reason it is difficult to discern piloting techniques is that they greatly differ based on what type of aircraft the pilot is used to flying, how much experience the pilot has, and even what aircraft carrier the pilot is used to landing on. For example, there have been significant technique differences noticed between pilots used to aircraft with different engine responses, pilots used to using auto-throttles or not, and pilots used to carriers with different degrees of air wake.

There are two general strategies used by Naval pilots during carrier approach. The first and simplest is the compensatory strategy where one control is used to control each error loop separately. The primary use of the compensatory strategy is with the backside technique where throttle controls altitude, longitudinal stick controls angle of attack, and lateral stick controls back angle. The longitudinal stick loop, for example, could be represented as

$$\delta_s = K_c(\alpha - \alpha_{desired}) \tag{4}$$

where δ_s is stick command, α is angle of attack, and K_c is an element such as a gain or a lead-lag compensator. The back-side technique is simple and tends to minimize angle of attack excursions when making altitude corrections. Yet, for faster, more precise altitude corrections, the front-side technique that uses longitudinal stick to control altitude and throttle to control angle of attack may be used. With the compensatory front-side method, however, it is difficult to maintain constant angle of attack. Therefore, a pursuit strategy is often used instead of a compensatory one. In the pursuit strategy, there are crossfeeds to decouple controls. For example, when putting in a stick change to alter sink rate, a feedforward throttle command would be put in to maintain angle of attack. Thus, longitudinal stick commands for the pursuit front-side technique might be

$$\delta_s = K_{p1}(\dot{h} - \dot{h}_{desired}) + K_{p2}\delta_t \tag{5}$$

where δ_s and δ_t are stick and throttle commands, $\dot{h}$ is sink rate, and K_{pi} are compensation strategies. For purely manual approaches, experienced pilots use the back-side pursuit technique most of the time. The front-side technique is usually only used with an auto-throttle that maintains constant angle of attack. This is because, while the front-side technique allows more aggressive glide-slope regulation, it is much more difficult for the pilot. Nonetheless, some pilots do favor using the front-side technique in specific situations when fast, precise altitude changes are required. This mainly happens in the last 15 seconds of the approach, when deck motion must be dealt with.

When using either strategy, pilots typically begin with a large control input, back off the control as the desired state is approached, slightly increase it as rates stabilize, and so on. These corrections are not always applied in a constant manner. The overwhelming response of pilots to questions on providing successful error regulation was that the primary concern should be for developing trends and not for steady-state errors, within certain bounds. For example, pilots and LSO's were generally unconcerned with small errors above glideslope and with small errors in speed and lineup if sink rate, drift rate, and acceleration are acceptable. The one exception to this idea is the below glideslope condition, where pilots state very strongly that no low error is acceptable. Pilots also indicated that control actions vary based on the environmental conditions. For example, in smooth air and calm seas, pilots can fly with minimal inputs and often used the backside pursuit technique for the entire approach. With large vertical gusts and carrier motion, pilots sometimes prefer the front-side technique to make small rapid changes. Also, for poor weather conditions, pilots use more of an averaging technique to deal with errors, except for low conditions that are dealt with quickly. Dealing with the carrier air wake is usually done by a quick pulse of throttle input, particularly for aircraft with good engine response like the F/A-18. For dealing with significant carrier motion in the final stages of the approach, it was very unclear from conversation how this is done. Too much is based on quick pilot reactions and on LSO's excellent abilities to predict carrier motion and judge aircraft responses visually.

Also, this is a region where pilots might perform a technique considered unsafe such as deck-following with bang-bang control and would therefore be reluctant to discuss it. Thus, understanding techniques used for this part of the approach was out of the scope of this thesis and will likely require a study conducted on actual carrier decks.

3.2 Automatic Carrier Landing Systems

Automatic carrier landing systems(ACLS) handle landing much differently than pilots. The basic requirements for an ACLS are that they be robust to turbulence, have high bandwidth tracking, and can handle the following ship motion: 1.25 deg. rms pitch, 5 deg. rms roll, 4 ft. rms heave, 20 ft. maximum vertical motion, and 1/4 deg/sec. heading changes at 30 knots

Within these boundaries, the ACLS must have a landing dispersion of less than 40 ft. longitudinally, and 15 ft. laterally. An ACLS also has to remain within certain bounds or it is forced to disengage. The F/A-18 ACLS must maintain angle of attack, roll angle, and aircraft position within certain ranges. Also, all ACLS systems have limited control authority so the pilot has time to manually disengage if there is a failure. For the F/A-18, the limits are placed on maximum pitch and bank angle rates.

An ACLS consists of a number of components as shown in Fig. 7. One of the main ones is a ship-board tracking radar and digital computer to measure aircraft position and calculate pitch and bank steering commands. These commands are sent to the aircraft's autopilot, which determines appropriate control responses to meet the commands. For the F/A-18, there may be delays of up to 200ms since the ship's link to the aircraft is over the aircraft's 1553 multiplex data bus and via the aircraft's mission computer. The last component of the ACLS system is the Approach Power Compensation System or auto-throttle. This component sets the throttle to maintain constant angle of attack. It operates independently of the other parts of the system, except for using stabilator position and roll to perform feedforward compensation similar to the pilots pursuit strategy for angle of attack regulation.

The F/A-18 longitudinal autopilot uses Inertial Navigation System sink rate and vertical acceleration to set stabilator actuator commands to get desired sink rate. Studies have shown dramatic improvements, particularly in gust rejection, over ACLS's that do not use vertical rate feedback. In addition, pitch rate feedback is used to provide an inner loop with higher gain amplitude in the 2-30 rad/sec range than the inner loop used by the pilot. Also, angle of attack is used to schedule leading edge flaps. The F/A-18 lateral autopilot component is similar to the longitudinal component with an inner roll loop and an outer loop that compares roll feedback to roll command. An additional feature of the ACLS is that at 10-13 sec. before touchdown, deck motion compensation is added to the glide-path tracking command to add a lead component from the deck position measurement sensors. This is the only way carrier motion away from the stabilized glideslope is incorporated.

The APCS component on the F/A-18 is not a simple angle of attack loop. The APCS uses normal acceleration, pitch rate, stabilator position, and bank angle inputs. Normal acceleration and pitch rate are used to improve angle of attack regulation. Stabilator position and bank angle are used to provide feedforward compensation for turns and pitch maneuvers before they can substantially affect angle of attack.

4. SIMULATION TESTBED

The F/A-18 is a Naval twin-engine high performance jet aircraft with all-weather intercept and ground attack capabilities. This aircraft is controlled primarily by ten hydraulically actuated surfaces. These primary surfaces are dual rudders, ailerons, leading edge flaps, trailing edge flaps, and stabilators. Inputs to the actuators are provided by two flight control computers through a full authority control augmentation system. These computers can use all ten surfaces to their best benefit. For example, besides ailerons, differential flap and stabilator as well as a rudder interconnect can be used to improve roll performance. On landing approach, however, differential flaps may not be used and differential stabilator can only be used when it does not interfere with its primary use as pitch control. Similarly, longitudinal control may not use not only stabilators and flaps, but also more unconventional control surfaces such as asymmetric rudder deflection.

The simulation testbed was a 386-based F/A-18A six-degree-of-freedom non-linear carrier approach model. The required characteristics for the simulation was to have representative complexity and limitations of an actual F/A-18 on carrier approach. Toward this goal, the simulation was augmented for this thesis with more realistic sensor, actuator, engine, noise, and disturbance models. These are necessary, since otherwise, the fuzzy logic system was capable at some times of producing clearly unrealistic behavior, such as virtually instantaneous angular decelerations.

The simulation block diagram is shown in Fig. 8. The aerodynamic model is a linear perturbation model with scheduled parameters to introduce aerodynamic non-linearities. This model is in standard state space form

$$\dot{x} = A(x)x + B(x)u + G(x)v \tag{6}$$

where x is the state vector, u is the control vector, and v is the disturbance vector. This is sufficient since the major causes of aerodynamic non-linearities are changes in angle of attack, sideslip, speed, altitude, Mach number, aircraft weight, and center of gravity. Thus, since these quantities are relatively constant during approach, the major non-linearities relate to aircraft components, such as data transmission delays, and actuators and engine performance. The actuator models are third order sub-systems with rate and position saturations. Different actuator models are used for the stabilizer, rudder, aileron, leading edge, trailing edge, and approach power compensation actuators. The engine model is a sixth order sub-system also with rate and position saturations. The sensor models are all first order lags, except for air data parameters and ship-board measurements. Air data parameters have a 50ms delay to model computational lags and ship-board measurements have a 100ms delay with a randomly varying 0-50 ms delay to also model lags due to asynchronous processors. Sensor noise is additive Gaussian white noise, except for velocity and aircraft position measurements from ship-board radar. Velocity has multiplicative noise and aircraft position has a first order random walk for each component of noise. Sensor noise and dynamics are also passed through an anti-aliasing filter to avoid unrealistic sensor behavior. There were four types of disturbances that are simultaneously applied to the system. The first is the standard Dryden continuous turbulence model from MIL-F-8785C. This model has first order dynamics and is driven by white noise. For simulation, the amount of turbulence can be set at light, moderate, or severe. The second disturbance is a carrier motion model. Sinusoidal motion in pitch and heave dominate the sea-state model, with heave lagging pitch by 90 degrees. This model also can be set at light, moderate or severe. There is some random narrow band noise put in the carrier motion model to prevent unrealistic prediction capabilities. The other two disturbances are the deterministic and random components of the carrier air wake or burble. The deterministic part is a complex function of range to carrier and carrier motion. The random part is a first order dynamic system driven by white noise whose parameters also change as a function of range to carrier and carrier motion.

5. DEVELOPMENT OF FACLS

The Fuzzy Logic Automatic Carrier Landing System is designed only to provide a Mode I fully automatic approach. It also only controls the final leg of the approach from tipover to touchdown. It is assumed that gear and flaps have been extended, the aircraft is close to approach speed, and the wings are close to level. To provide a fair comparison with the current F/A-18 carrier landing system, the FACLS is constrained to have most of the same limitations. As described in Section 3.2, it has to disengage beyond certain glideslope errors and angular attitudes, and it has limits on allowable roll and pitch rates. The FACLS also only uses inputs that are available to current ACLS systems. The one advantage the FACLS has over the current ACLS system is that the FACLS has the potential to be a more coupled controller since it combines the ship-based ACLS system, the aircraft auto-pilot, and the auto-throttle. As described in section 3.2, these are combined in current systems to a lesser extent. The current ACLS, however, has an advantage over the FACLS since it uses specially designed inner loops. The FACLS, on the other hand, has to rely on a modified version of the manual control inner loops.

There are eleven inputs used in the FACLS. These are vertical glideslope position, sink rate, vertical acceleration, angle of attack, pitch rate, normal acceleration, range to ideal carrier touchdown point, lineup(horizontal position errors), drift rate(rate of change in lineup), roll rate, and roll angle. All inputs but range are broken into seven triangular membership functions. The seven membership functions represented OK and small, medium, and large deviation from a nominal value in each direction. Triangular functions were chosen since they are computationally simple, and trapezoids would not yield precise enough changes in ACLS outputs. Some experimentation yielded no benefit from other more complex membership functions such as Gaussian curves. Before tuning, the size and location of the membership functions were based on what pilots and landing signal officers would consider to be within these ranges. One example of this is for angle of attack, which is shown in Fig. 9. The membership functions in Fig. 9 are very fast, fast, slightly fast, OK, slightly slow, slow, and very slow(pilots refer to angle of attack in terms of fast and slow due to its relation to speed during carrier approach). As described later, these membership functions were altered during simulation and tuning. The one FACLS input that does not use triangular membership functions is range to carrier. This input space is divided into four trapezoidal membership functions as shown in Fig. 10. Using four trapezoidal membership functions is adequate since some membership functions vary as a function of range. This means that the range membership functions are mostly used for altering control strategies, and not for altering control magnitudes. One input with variable membership functions is glideslope error. The membership functions for glideslope error are scaled so that the highest value of the large membership functions in each direction is at the exact boundary to disengage.

The outputs of the FACLS are longitudinal stick position change, lateral stick position, and throttle position change. These are not ideal, but are used to keep rules transparent to pilots. Throttle output is the only true physical quantity since it goes directly into the approach power compensator actuator. Stick outputs, however, are not physical quantities, but idealized values that would be implemented in the flight control computer. This overcomes the limitations of an actual stick, such as deadband non-linearities, and allows some modification of the

F/A-18 inner loop control law. Each of these outputs is broken into 19 equal sized triangular membership functions. Nineteen was found through experimentation to be sufficient to get the necessary variety of outputs.

The rule base was developed in two parts. In the first part, a set of rules was determined based on the current state of the art F/A-18 ACLS system, Navy ACLS requirements, research reports on how to improve ACLS systems, and discussions with Navy flight controls engineers. This yielded a set of rules roughly similar to a very complex gain-scheduled automatic feedback control system. Following this, a set of rules was put together based on discussions with Naval pilots, literature on piloting techniques, and Naval Flight Procedures. Developing these rules was one of the most difficult parts of this study due to the difficulty in determining pilot strategy through conversation as described in Section III.

After building both rule bases, these were combined to yield an optimal control strategy. Pilot rules based on human limitations such as the inability to monitor many sensor inputs at once or poor response times were eliminated. Other pilot rules based on non-accessible cues such as visual or auditory ones were eliminated or modified so they could be used by an automatic system. Automatic control rules, on the other hand, were often constrained to keep system complexity or design and development effort reasonable. This allowed many rules to be changed or modified to be more in spirit with the pilot rules. Also, given the ease with which complexity could be added to fuzzy rules, many were modified to be more sensitive to prominent pilot concerns, such as dealing quickly with low conditions and being more concerned with trends than small steady-state errors. The final set of rules was largely based on good automatic techniques that had been augmented to incorporate useful pilot techniques and prominent pilot concerns.

This final rule base would need more than five thousand rules for implementation in a pure fuzzy logic controller. Yet, many control strategies could be expressed as standard control loops. Therefore, the fuzzy controller was designed as a classical control structure with five blocks containing individual fuzzy rule bases as shown in Fig. 11. Each of these rule bases is described in Section 6. The glideslope rule base controls glideslope position and sink rate using longitudinal stick, and also outputs a command proportional to throttle that maintains angle of attack during glideslope changes. The alpha rule base operates much like the F/A-18 APCS to control angle of attack with throttle. It also outputs a feedforward command to longitudinal stick to maintain sink rate during throttle changes. The longitudinal stick command passes through a first order lag due to the difference in bandwidth between engine and stabilator responses. The lineup rule base outputs a desired bank angle to control lineup and drift-rate and has a similar function to the lateral part of the ship-board ACLS computations. After passing through a limiter, the roll rule base uses this bank command to output lateral stick commands to control roll angle and rate. It also outputs throttle and longitudinal stick commands to maintain angle of attack and sink rate during maneuvers. The final rule base contains all rules that could not be decoupled and is mainly concerned with close in where allowable control deflections are limited and a more coupled strategy must be used for best effect. With this structure, the system required only about 400 rules. There is probably a better way of performing carrier landing by using only one rule base and not decoupling the problem at all. Still, determining this is very difficult since both control designers and pilots use the decoupled approach. Also, it was not possible to derive fuzzy logic rules using, for example, a neural network technique, since there was no easy way to determine a good cost function for criteria such as pilot acceptance.

Each fuzzy rule base has the same functional description. The fuzzification method for each system is function calculation instead of table look-ups due to the size of the rule base, the need for precision, and the quick calculation possible with piecewise linear membership functions. AND and OR are defined by the standard Max and Min as described in Section 2. The defuzzification method is the centroid procedure, which is required for a true weighted combination of activated rules. For encoding, Max-dot is used since it worked better in some situations than the Max-min method. The primary reason for this is that for triangular membership functions, Max-dot gives stronger weighting to the most heavily weighted rules. Based on these results a new encoding method that squared the degree of activation and multiplied the output membership function by it was attempted. This seemed very promising for some types of control problems.

The FACLS and aircraft model were both programmed in the Borland Integrated Development Environment using C and C++. The mathematic's program, 386-Matlab was used to interface between the different programs. In the FACLS software each input variable was considered to range from -1000 to 1000 or 0 to 1000. Matlab handled all interfacing including scaling sections of the input variable space to each piecewise linear segment of the membership functions. This enabled quick adjustment of input membership functions without having to constantly recompile the code or provide many inputs to the C and C++ code. Further, Matlab's capability of calling the user as a sub-routine allowed very efficient "on-line" tuning during a simulated approach. Two main trends arose in much of the tuning. One trend was the decrease in the size of membership functions near zero error with the corresponding increase in ones further out. This allowed better precision for smaller errors. The second trend was many inputs ended with non-symmetrical membership functions about zero error. The tuned membership functions for angle of attack are shown in Fig. 12, which can be compared with the original ones in Fig. 9.

6. RULE BASE DESCRIPTIONS

The roll control rules will be examined first. This is the simplest rule base because it is least effected by range to carrier and has the smallest number of inputs. The final roll control rules are given in Table 1. They use roll error, roll rate, and range to carrier to provide a lateral stick command. Note that a stick position command is outputted as opposed to a change in stick position command since lateral stick commands roll rate, not roll angle. Rules 1-6 implement a proportional gain controller for large through small errors between desired and actual roll rate. Rules 7-12 supply some derivative action to increase control action if the roll rate is highly adverse on small and medium errors. Note that this derivative action can only increase commands and is not used to supply damping as is done with rules 13-19. Rules 13-19 implement derivative action to null roll rates when the error is near zero. This switching in of varying degrees of derivative action throughout the maneuver allows rapid responses with minimal overshoot. Finally, rules 20-21 provide some derivative action for damping during the final wing leveling if roll errors are small and roll rates are large. The activation of rules 20-21 in the "close in" range allow wing leveling in the quickest possible time. Without rules 20-21, gross errors in lineup can be altered more quickly, but achieving zero roll angle takes longer due to a small amount of overshoot. The final rule, rule 22, is to end all lateral stick inputs in the "at ramp" range. It is important to note that rule 22 is blended in over a small range, so initially it just begins decreasing potential stick action until it is fully implemented at 300 ft. from the landing point and motion is frozen.

The lineup rules use lineup position, drift rate, and range to carrier to output a desired roll angle. The lineup rules are much more complex due to the way they vary with range to carrier, and the nature of lineup changes. The "at start" rules are very similar in spirit to roll rules 1-19, since the "at start" range is the only one at which large lineup errors have time to be corrected. However, for this range, their are many more lineup rules than roll rules. This is because all lineup rules need to consider drift rate as well as lineup. By the "in middle" range, it is too late to make any large corrections in lineup. It is better to insure drift rate in adverse directions has been nulled or at best make one small correction early in this range. Thus, the "in middle" rules use even more derivative action. There is only one "in close" rule and that is return to wings level. It is important in understanding how these rules work, to remember that ranges are not described as exact categories, but as shown in Fig. 10. Thus, up to 3500 ft. "at start" rules are still active, although they are moderated by "in middle" commands that decreases the maximum size of alterations and add much more derivative action to null drift rates. Similarly, the "in close" rules begin being blended in at 2500 ft. and therefore create an increasing tendency toward wings level by the "in middle" rules. Further, the "in middle" rules that control drift rate do not completely cease being active until 1500 ft., allowing small alterations well into what is considered the "in close" range.

The angle of attack rules use angle of attack, normal acceleration, pitch rate, and range to carrier to output changes in throttle position. This change in throttle position is combined with proportional values of lateral and longitudinal stick commands to provide the final change in throttle position command. This rule base is similar to the roll control rules, except it uses both normal acceleration and pitch rate to provide damping. Differences between throttle control rules and roll control rules appear mainly in the "close in" and "at ramp" range and are contained in the coupled rule base. Thus, this rule base's theory of operation is very similar to the current F/A-18 Approach Power Compensation, although it has a somewhat more complex non-linear control strategy.

The longitudinal glideslope control rules are form most complex rule base of the four main decoupled bases. This rule base uses vertical glideslope position, sink rate, vertical acceleration, and range to carrier to generate changes in longitudinal stick commands. This command is then combined with outputs of roll and angle of attack rules to give a final change in longitudinal stick command. The primary strategy used by this rule base is the pursuit front-side technique, since the benefits far outweigh the disadvantages for any system with good automatic control of angle of attack. These rules are also changed based on range to carrier. For the "at start" range, this is the only time at which large errors are allowed and they must be accommodated quickly. This is done using rules very similar to rules 1-19 of the roll control rule base. Rules for large errors operate like high gain proportional controllers. As the error gets smaller derivative action is used to create a well damped system. However, unlike the roll control system there are rules which decrease commands based on rates. For example, small errors tend to be ignored if there is a decreasing trend and they will shortly be nulled. At the "in middle" range, as with lineup rules, a primary concern is nulling any adverse rates in vertical rate or acceleration. However, unlike lineup, one category of position errors is taken very seriously. These are low errors. Thus, responses are not symmetrical about glideslope. Low conditions are dealt with very rapidly, even if it means accepting some overshoot. This is because a high condition, may still catch the number four wire, and may be corrected anyway during settling in burble. This reasoning is carried through with regard to rates, where any fast sink rate or acceleration tendency is dealt with quickly unless their is a significant high condition.

Closer in, the problem changes since instead of a stabilized glideslope, carrier motion must be accommodated. All compensation of deck motion is done by the fifth and final rule base, the coupled one. This rule base has all the inputs and outputs of the other four rule bases. It can also choose either to add to their commands or to replace other rule base's commands with its own. Usually, for deck motion compensation, this rule base just adds to the other commands that are based on a stabilized glideslope. However, very close to touchdown, this rule base may exert complete control of the aircraft. This is usually done to make very small combinations of throttle and stick to correct an error, as opposed to the more decoupled strategies used further out. The coupled rule base also has commands for other strategies. For example, when flying into the deterministic part of the burble, the coupled rule base adds some temporary throttle and stick to the other rule base commands to compensate for the burble's settling effect.

7. SIMULATION RESULTS

Both the FACLS and the H-dot system were tested over 200 approaches. The majority of approaches were with severe turbulence and sea-state conditions. The reason for this is that the F/A-18 system has excellent performance in calm and even moderate conditions and there is little room for improvement over its capabilities. For each weather condition, there was a variety of starting conditions, from dead-on glideslope to some errors just within the allowable boundary. As with weather conditions, most cases dealt with more difficult initial conditions.

Each landing attempt was classified as a wave-off, bolter, hard landing, ramp strike, excellent, acceptable, or poor.

A wave-off is a deliberately aborted landing attempt that is called by either the pilot or the LSO. Criteria for a wave-off is very subjective. LSO's often use inputs as difficult to measure as their knowledge of the pilot. Thus, the following criteria are relatively simple approximations of some of the more widely used wave-off requirements. They are conservative in some regards and liberal in others. One example of liberal behavior is shown by the number of ramp strikes, which are much more unlikely in real operations. A wave-off was considered to have been called if any of the following four conditions occurred:

1) The carrier landing system was required to disengage after exceeding the boundaries given in Section 3.2. In some ways, this criterion is tighter than LSO bounds. In others, it is looser.

2) There were more than two major deviations in glideslope, lineup or angle of attack when entering the "close in" range. Note that this does not include small steady-state, acceptable errors.

3) The aircraft had a high condition combined with a low sink rate in the "close in" range. This is often called a wave-off to prevent a hard landing or ramp strike due to over correction.

4) The aircraft had a low condition with a high sink rate in the "in close" range. If the aircraft had either a low condition or a high sink rate, a wave-off was called unless the aircraft's combination of sink rate and altitude made it probable that the aircraft could clear the ramp by more than seven feet.

A bolter was considered to have occurred if the aircraft cleared the ramp by more than 18 feet, unless the aircraft had a sufficiently fast sink rate. This was considered to be the boundary by many pilots for successfully getting the number four wire.

A hard landing was considered to have occurred if the aircraft landed with a sink rate greater than fifteen feet per second or a speed 15 percent above the nominal.

A ramp strike was considered to have occurred if the combination of pitch attitude with altitude at the ramp would cause the hook to strike the ramp.

An excellent landing was considered to have occurred if the aircraft landed with the proper pitch attitude, wings level, speed close to nominal, sink rate less than fourteen feet per second, lineup close to desired, and caught the number three wire.

An acceptable landing was considered to have occurred if the aircraft landed with wings level, sink rate less than fourteen feet per second, and acceptable speed and lineup.

All other landings were considered poor.

The results of the 200 landings are displayed in Table 2. The FACLS achieved a significant reduction in hard and poor landings, ramp strikes, and wave-offs. This yielded a substantially larger number of excellent and acceptable landings. Interestingly, the number of bolters was slightly increased for the FACLS. This is because the FACLS is much more concerned with low conditions and fast sink rates than high conditions. Thus, bolters increase, while hard landings decrease. It is important to note that in getting these results, two factors were tilted toward the FACLS. One factor was that there was minimal improvement for the FACLS in mild weather conditions. The improvements largely showed up during severe environmental conditions. Thus, FACLS improvements would not have been as good under a more typical distribution of environmental conditions. Also, it is important to note that some of this success of the FACLS is because the wave-off criteria and fuzzy logic rule bases were designed by the same person. Thus, the FACLS had an unfair advantage in avoiding unnecessary wave-offs, and in having its potential ramp strikes, and hard landings become wave-offs.

Despite these factors, the FACLS still clearly outperformed the H-dot system. There are two main reasons for this. The first reasons is the FACLS ability to make very rapid changes with very little overshoot. This occurred due to its ability to change control system gains and damping during a maneuver. An example of this is given for a glideslope correction in Fig. 13 and 14. Fig. 13 shows the return to glideslope with an incredible ability to make a quick return to nominal sink rate when the correction was finished as shown in Fig. 14. It is important to note that the FACLS makes the quickest glideslope correction possible without any threat of going low or acquiring fast sink rate. The H-dot system on the other hand had much poorer performance. A comparison of sink rate control between the FACLS and the H-dot system for another case is shown in Fig. 15. The FACLS has both better rise time at the beginning of the correction and better damping at the end, achieving its 5 ft/sec. change in minimal time. The H-dot system, on the other hand, has a slightly slower rise time, and pays for it with some overshoot in a temporary fast sink rate condition. One offshoot of this improved sink rate control is better control in turbulence. A comparison between the two systems performance in turbulence is shown in Fig. 16. This demonstrates the FACLS has much smaller deviations from glideslope. In general, the FACLS had about a 30 percent reduction in glideslope errors due to turbulence. A final example is shown for making a correction to drift rate. A comparison between the H-dot system and the FACLS for roll angle change is shown in Fig. 17. While the FACLS does not have as much improvement in this case, this is largely because of the limits on roll rate for carrier landing systems. Also, the current system does have some overshoot in lineup, which requires a much longer correction than the FACLS.

The second reason for the FACLS success relates to the difference in operating ideas. The H-dot system is designed to be very good at tracking glideslope and it is. However, the FACLS does not only attempt to track glideslope and maintain speed. Fig. 18, for example shows the FACLS in a slightly high position with a slightly slow sink rate going into the carrier air wake. In this condition, the FACLS with minimal control inputs allows the settling effect of the air wake to return the aircraft to glideslope and proper sink rate. In contrast, the H-dot system returns to glideslope and proper sink rate, and then implements a feedforward command to alleviate the effects of the air wake. Another example of this is Fig. 19. Here, the aircraft is at the start and the vertical glideslope error is not significant and decreasing. The FACLS then waits until intersection instead of wasting control power making a quick return to glideslope. A final example of this concerns a situation with a slightly high condition, but good sink rate in the latter stages of the "in middle range". Then, the FACLS maintains the high condition and catches the number four wire with an otherwise excellent landing at 14 ft/sec sink rate. In contrast, the H-dot system tries to correct this error and due to the high amount of vertical turbulence and ship motion ends in a hard landing at 19 feet per second sink rate.

In terms of control power used, the fuzzy logic controller commands higher rates more often, but ultimately requires less actuator motion due to its ability to do more than just track glideslope. The current ACLS is designed for high bandwidth tracking and disturbance rejection so it uses a great deal of control power. The FACLS is sometimes an even higher gain system, but is also sometimes a much lower gain system. What effect this would have on the aircraft's structure and the hydraulic actuation system is something that needs to be explored. There may be some benefits, for example, in including rules to lessen structural stress on the aircraft or reduce actuation rates in less critical situations.

A final question is whether the FACLS would improve pilot confidence. This question is impossible to answer without real-time simulation and flight testing. Further, the pilots interviewed in conjunction with this thesis all currently worked in a research and development or test and evaluation environment. Thus, their opinions may be different from the average fleet pilot. Also, it is uncertain if what pilots say they want on the ground, will still be as desirable when it actually happens in the air. Nonetheless, the results of this thesis have shown that it is possible to include pilot concerns with fuzzy logic. The main question is whether the ways it was incorporated in this thesis are correct. Thus, it is likely that pilot confidence could be improved with fuzzy logic control under a more substantial study(i.e. more money and more fleet pilot and LSO participation).

8. CONCLUSIONS

Thus far, fuzzy logic shows great potential for automatic carrier landing. The major benefits that were sought from fuzzy logic control were improved performance, improved pilot acceptance, reduced controller development times, and improved robustness. Of these benefits, some were clearly apparent, while others were either uncertain or unlikely. The one benefit that clearly occurred was an increase in performance. The excellent time responses of this highly non-linear controller combined with the use of some pilot heuristics clearly demonstrated substantial performance improvements over the current F/A-18 H-dot ACLS. While there are some minor differences between the two systems operating criterion, these are not significant enough to diminish the performance improvements noted. The performance improvement is particularly noteworthy since the FACLS could possibly exceed it by using more input data than the standard ACLS or through use of some form of on-line "learning". These results suggest that ultimately, fuzzy logic control may allow an expansion of operating conditions to more severe weather and sea-states. Similarly, pilot acceptance was clearly improved based on the criteria developed in this study. While this criteria might not improve acceptance for the average fleet pilot, it does clearly show the potential of fuzzy logic for doing so with a more thorough pilot study. In contrast to these two clear benefits, development time was not improved. The actual time spent developing the controller was decreased, but time spent in tuning was similar, and time spent in determining a heuristic model of how the FACLS should operate clearly increased. Quick development times with fuzzy controllers probably will only be the case when a good quantitative heuristic model of the controller's action is readily available. Finally, there are still questions about robustness and stability that need to be answered for the FACLS. Fuzzy controllers seem to have very strong static stability, in that they react to deviations from desired states with opposing forces. Still, there is some concern over whether changes or uncertainty in control surface effectiveness and aircraft response times will create residual oscillations, limit cycles, or even dynamic instability. Experience with tuning the controller has shown that these types of adverse behavior are possible even with an adequate rule base.

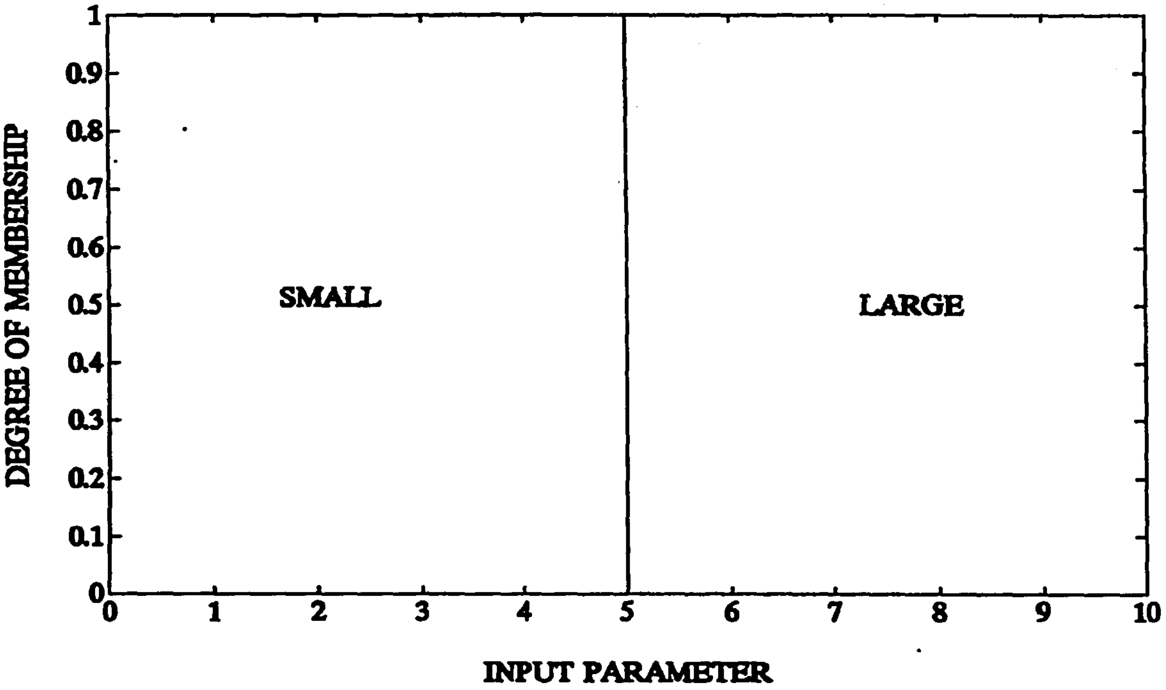


Fig. 1 Typical Classical Logic Categories

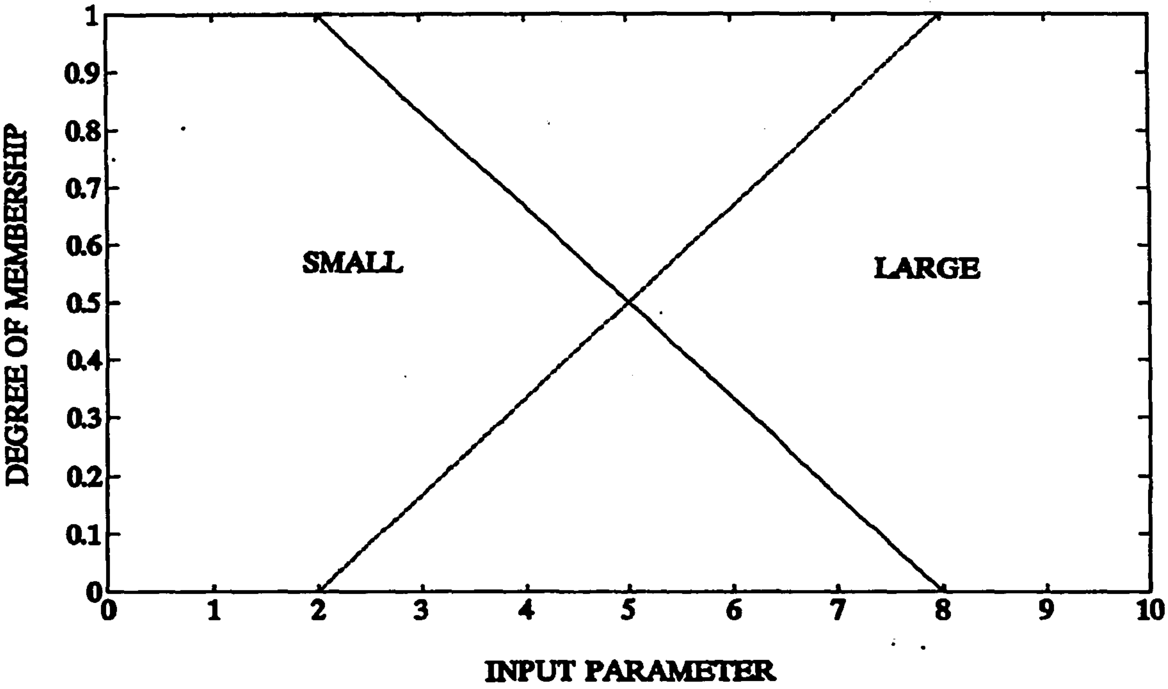


Fig. 2 Typical Fuzzy Logic Categories

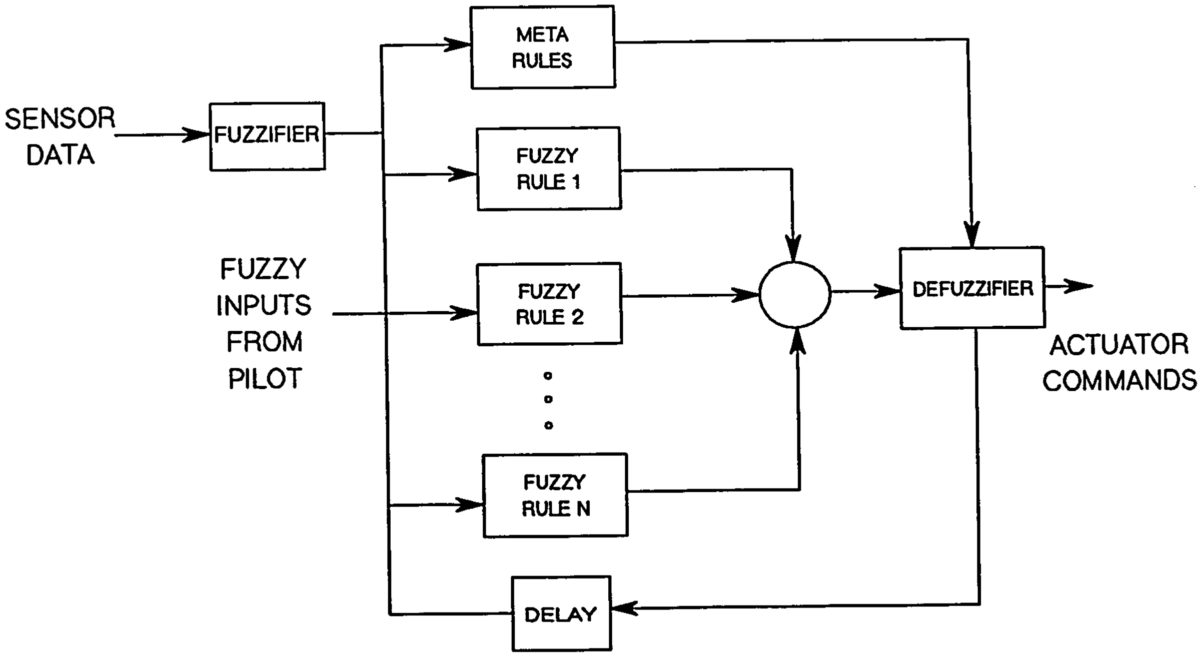


Fig. 3 Standard Fuzzy Logic Controller

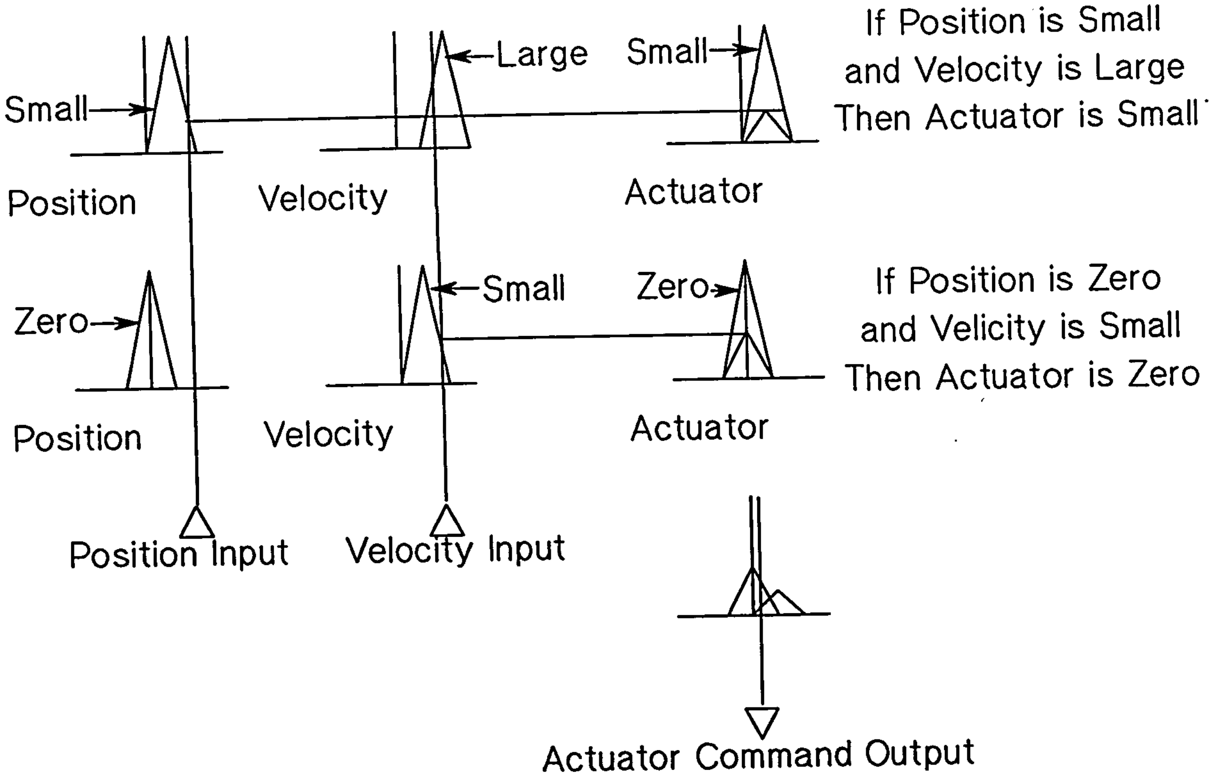


Fig. 4 Fuzzy Inferencing & Defuzzification

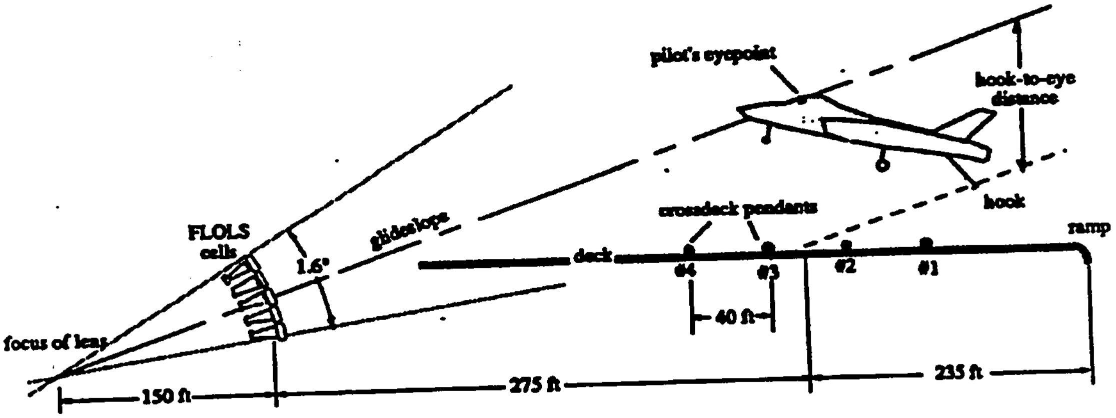


Fig. 5 Sideview of Carrier Landing

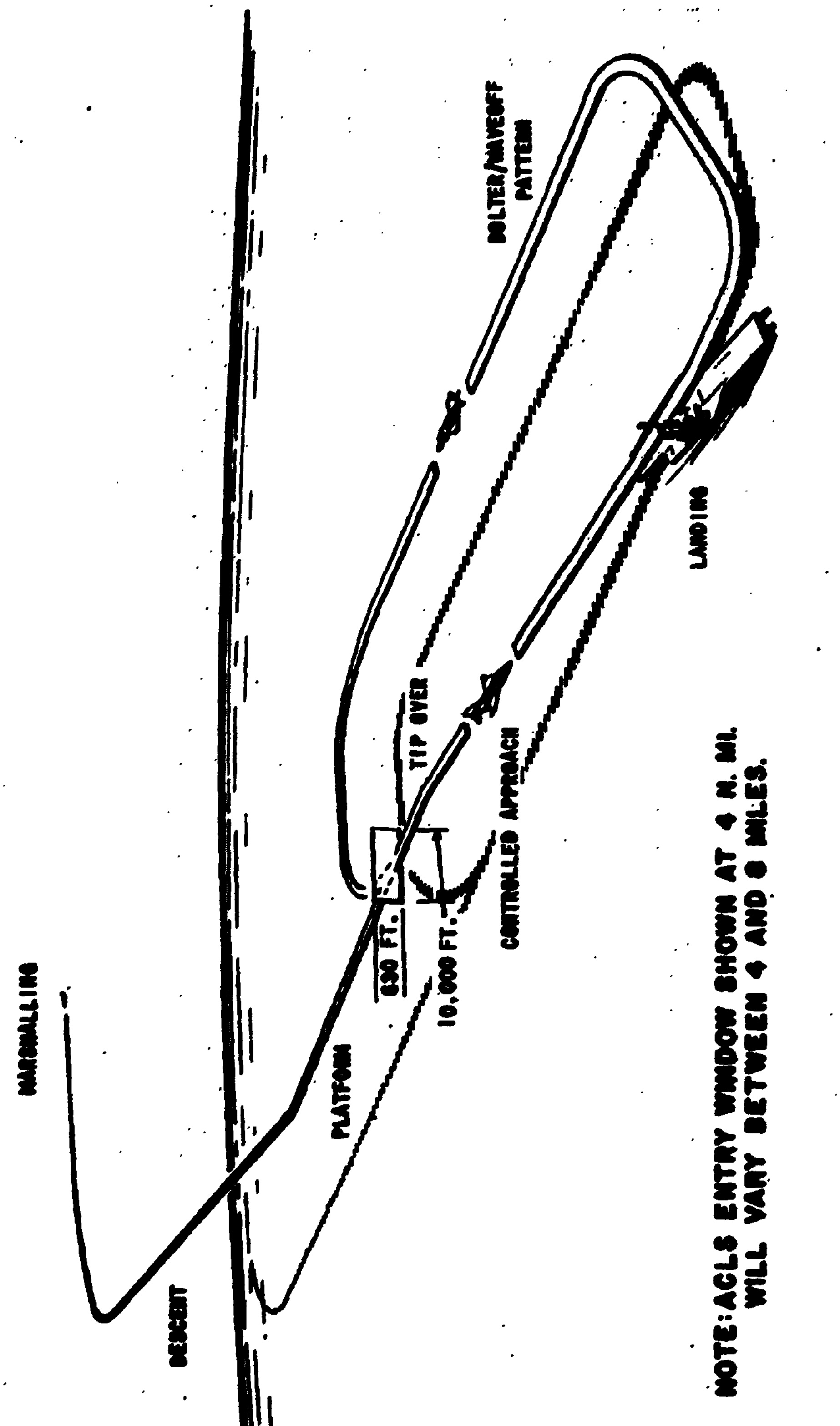


Fig. 6 Total Carrier Approach

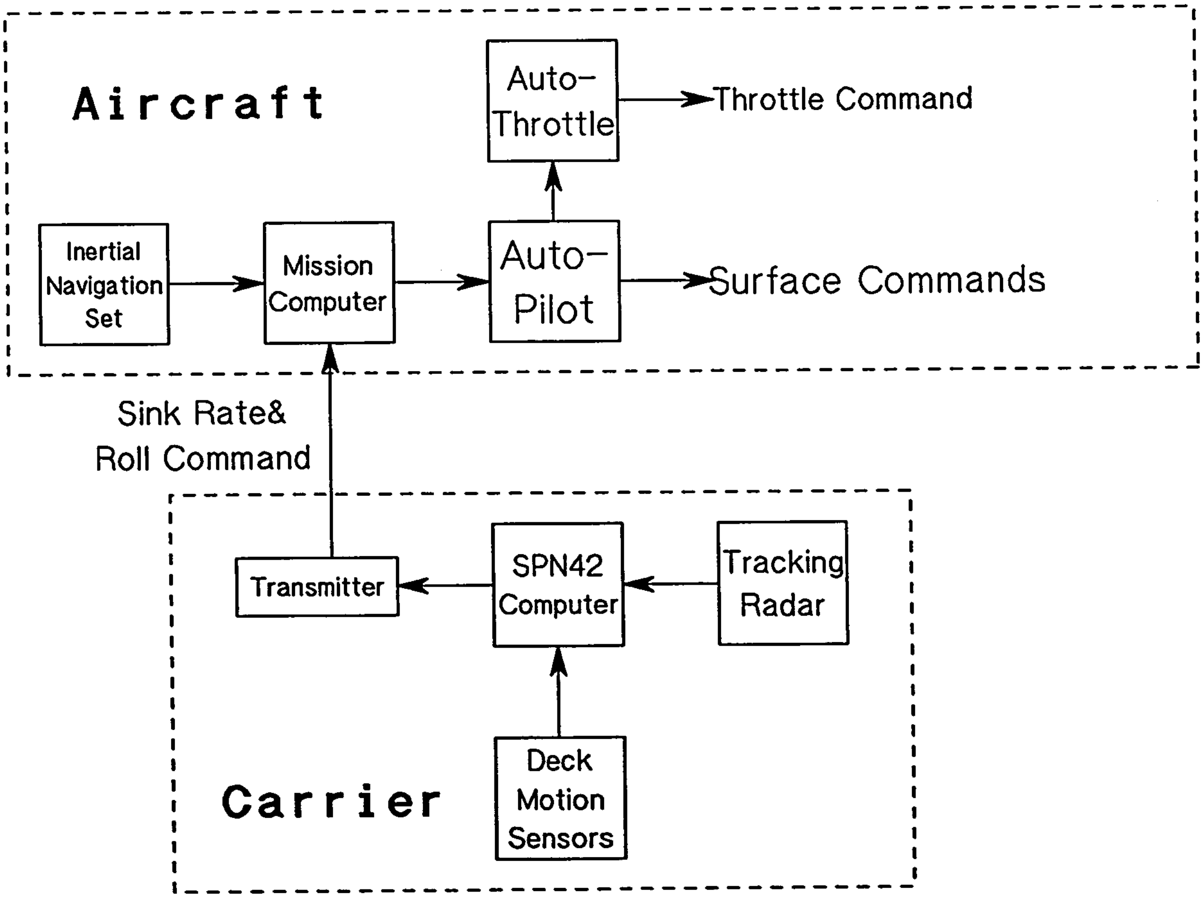


Fig. 7 F/A-18 Carrier Landing System

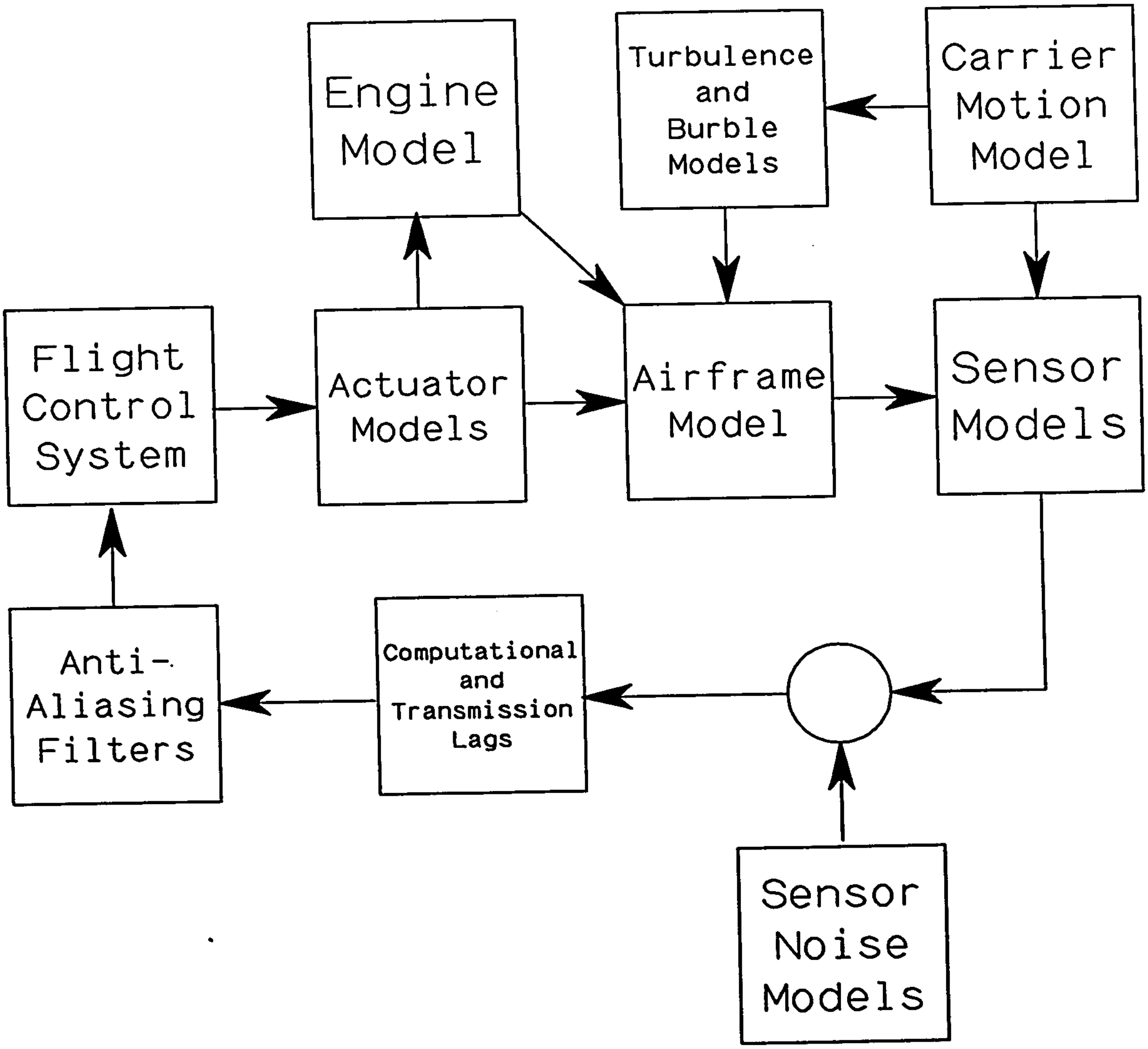


Fig. 8 F/A-18 Simulation Block Diagram

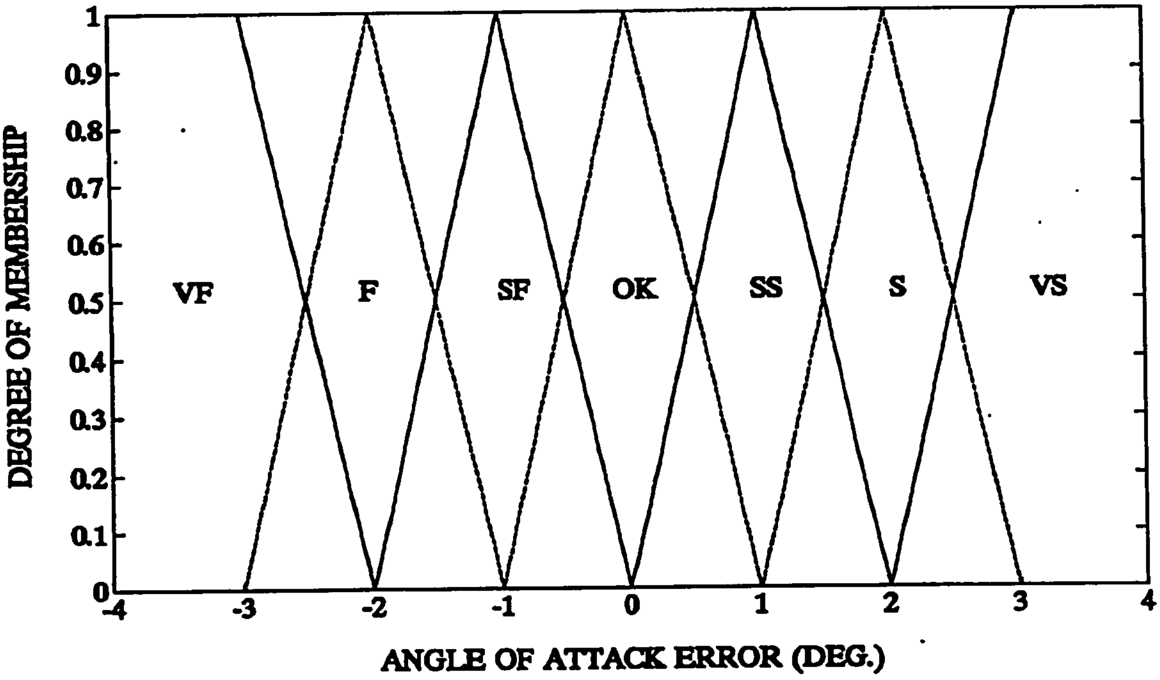


Fig. 9 Initial Angle of Attack Membership Functions

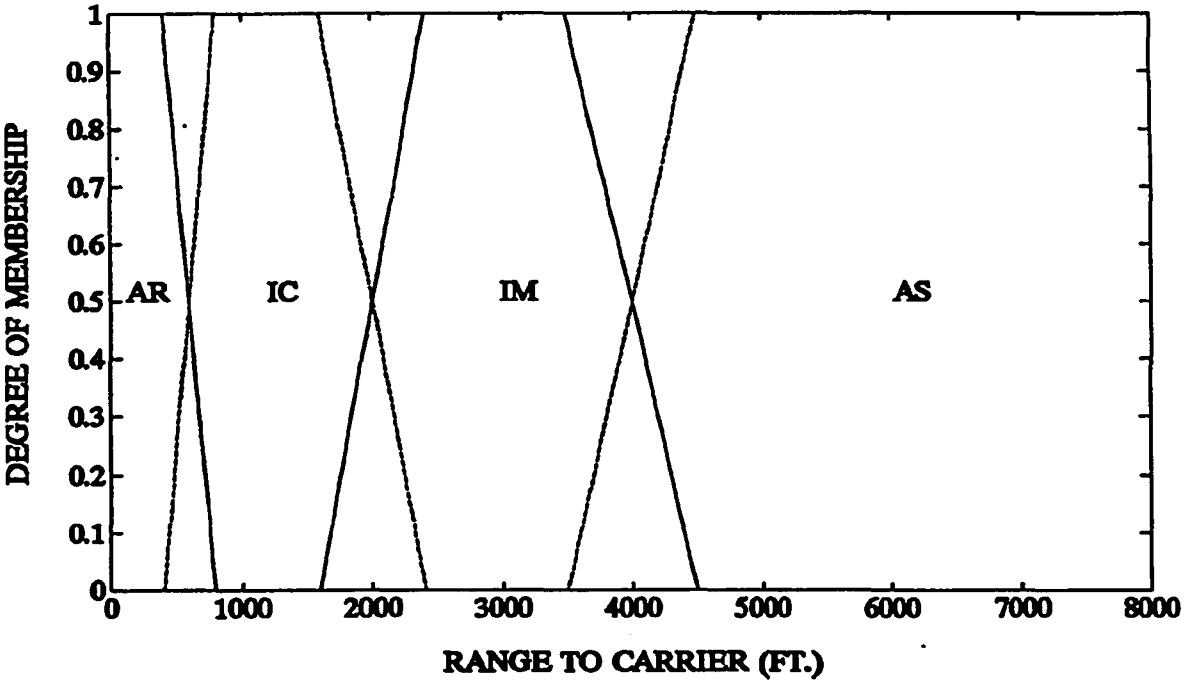


Fig. 10 Range to Carrier Membership Functions

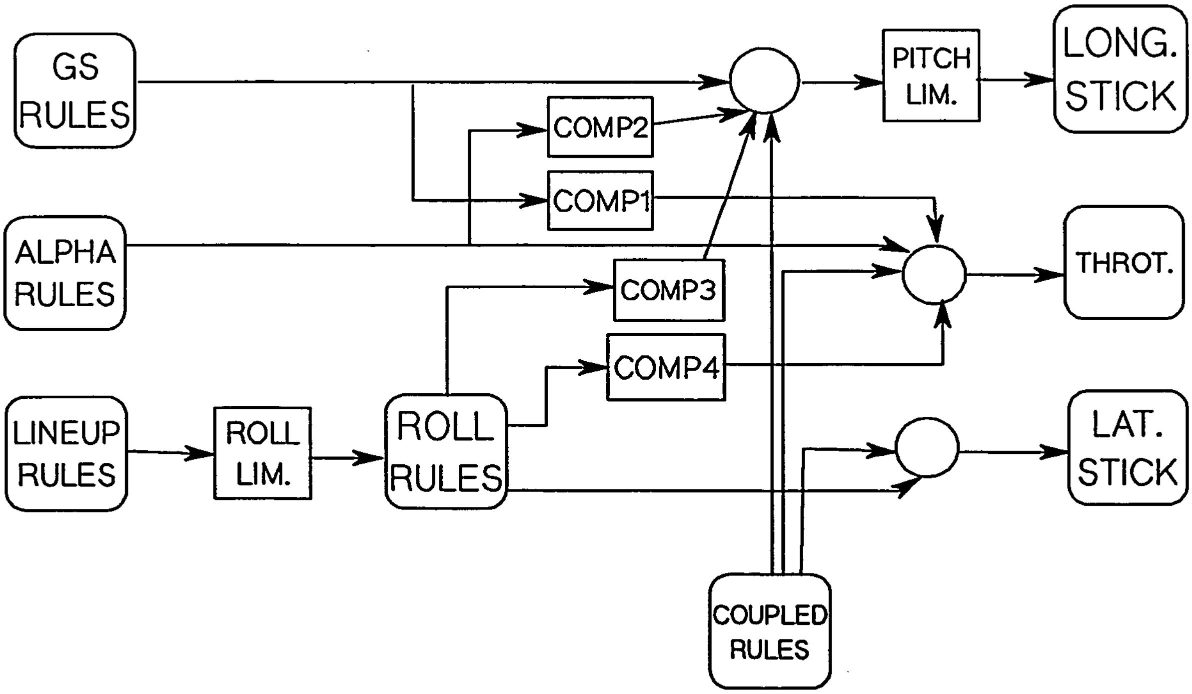


Fig. 11 FACLS Block Diagram

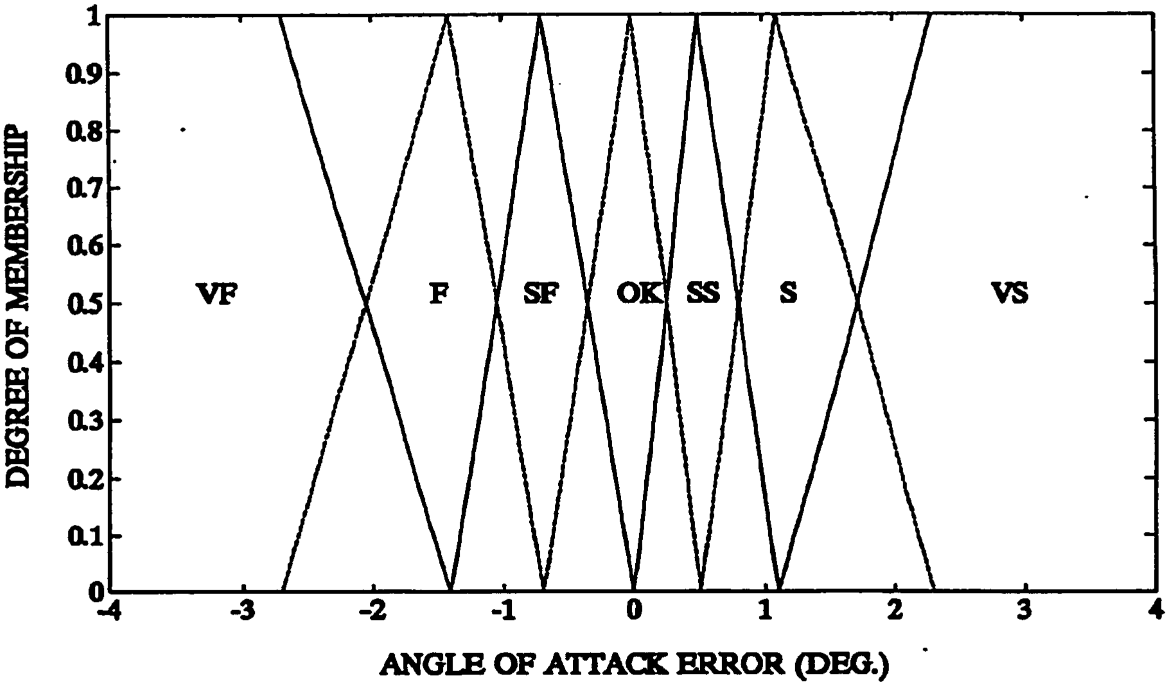
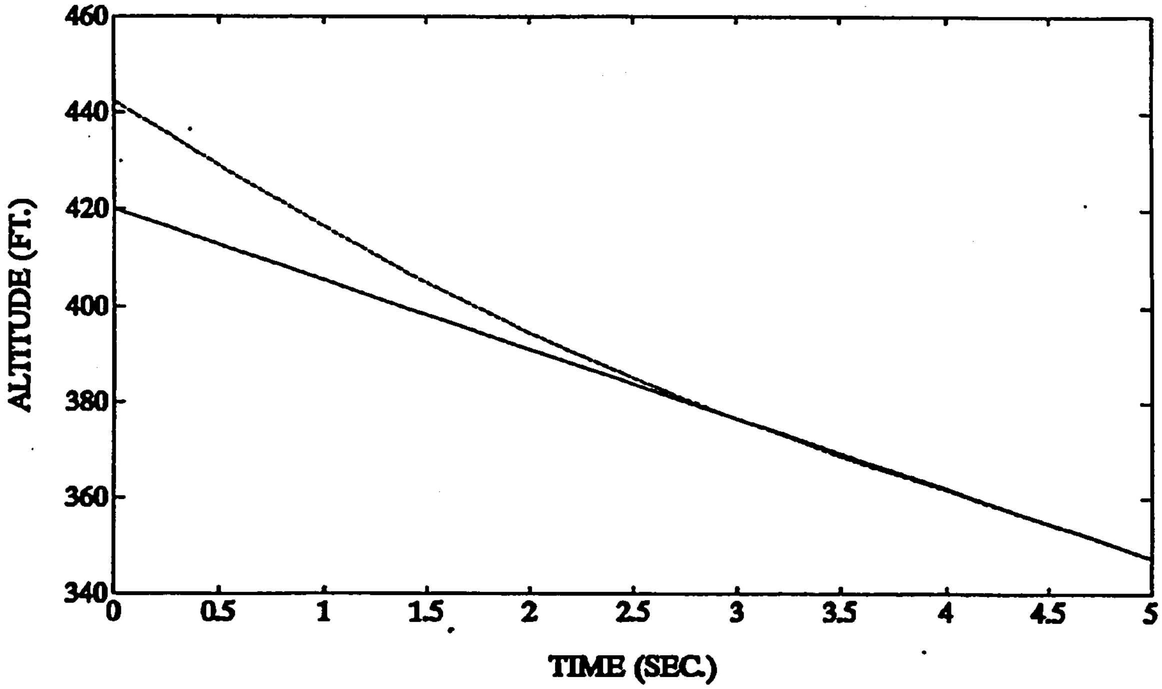


Fig. 12 Final Angle of Attack Membership Functions



Aircraft ------------

Glideslope_______

Fig. 13 FACLS Glideslope Correction

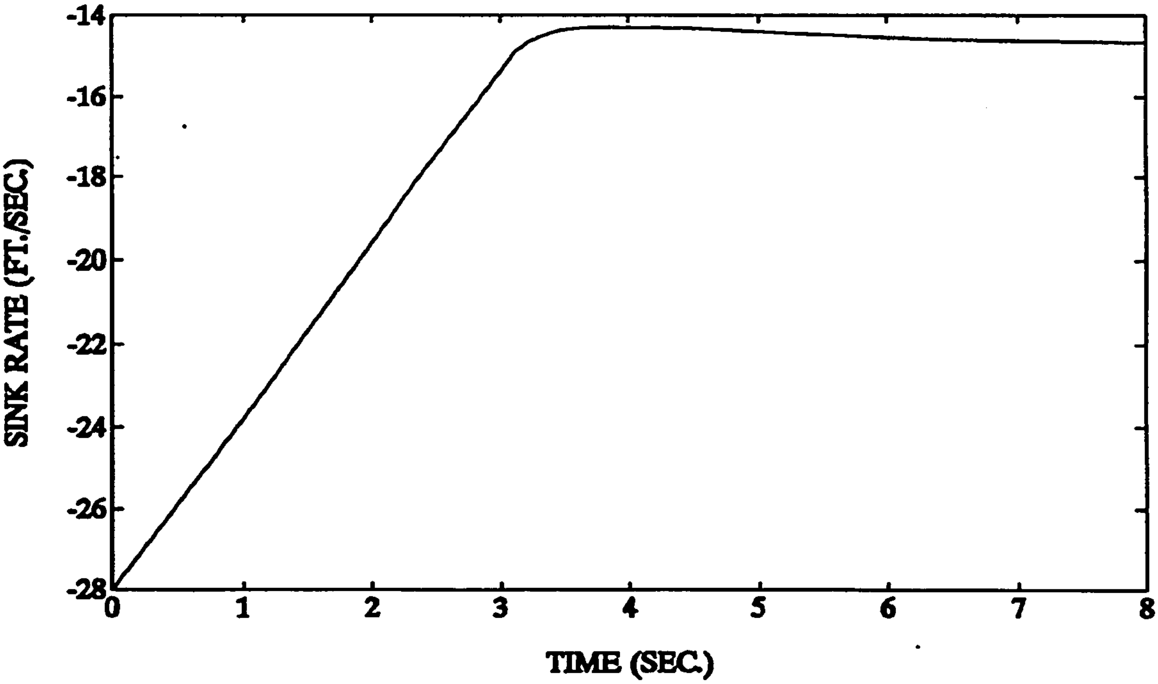
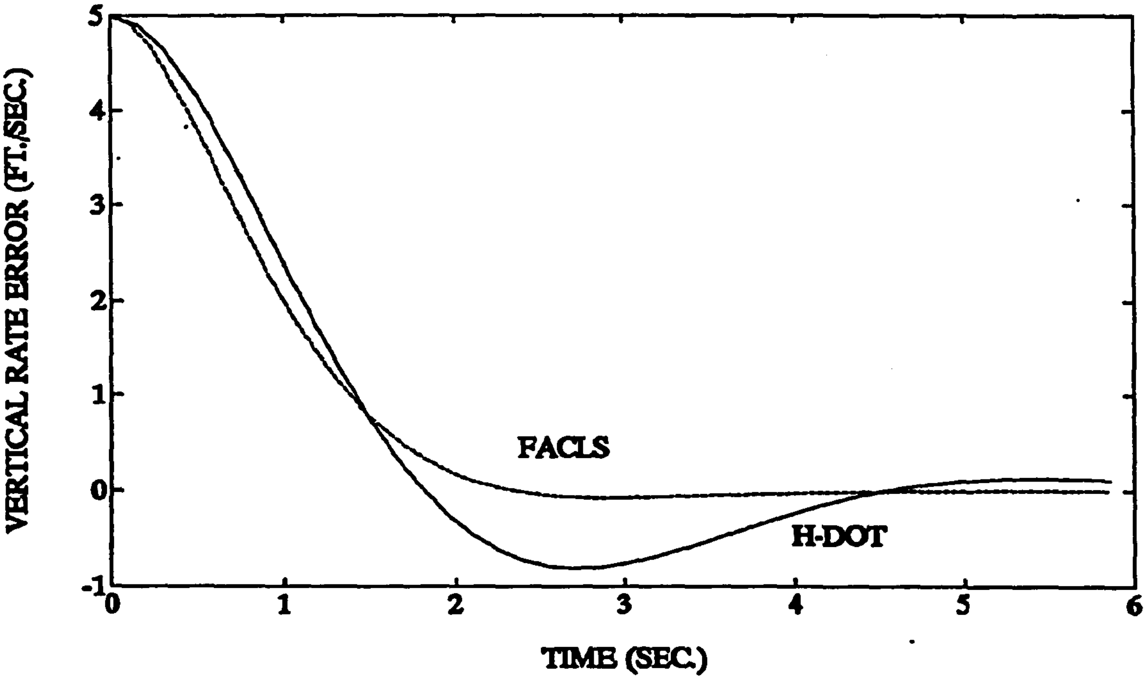


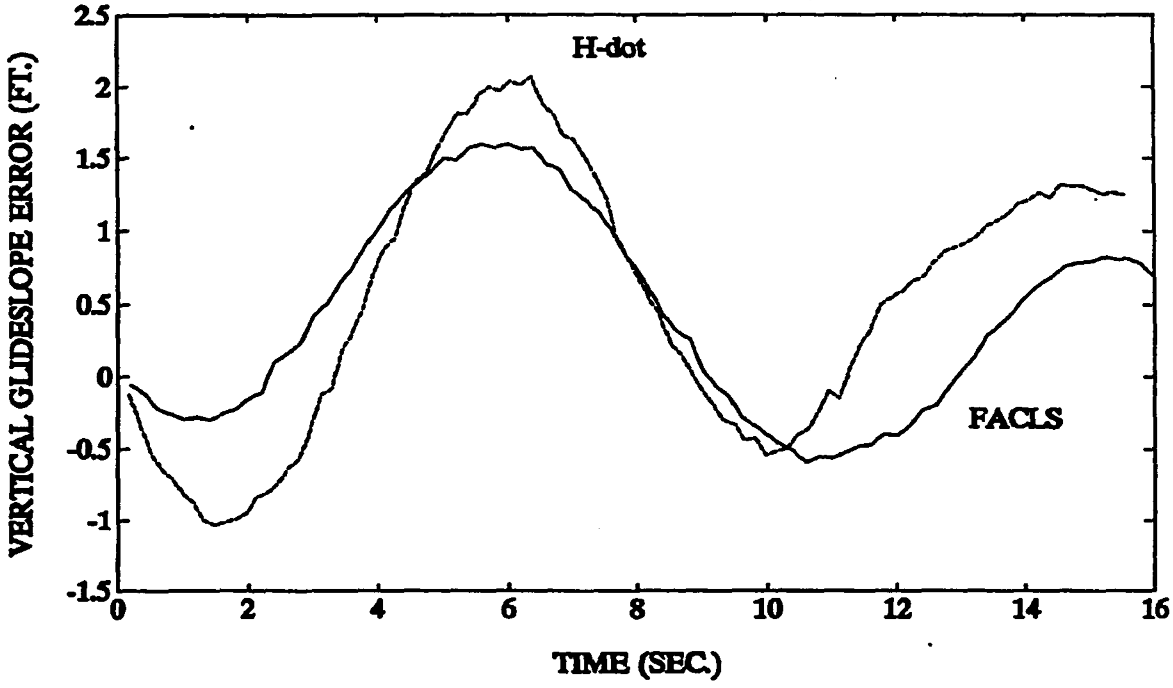
Fig. 14 FACLS Control of Sink Rate



FACLS ------------

H-DOT__________

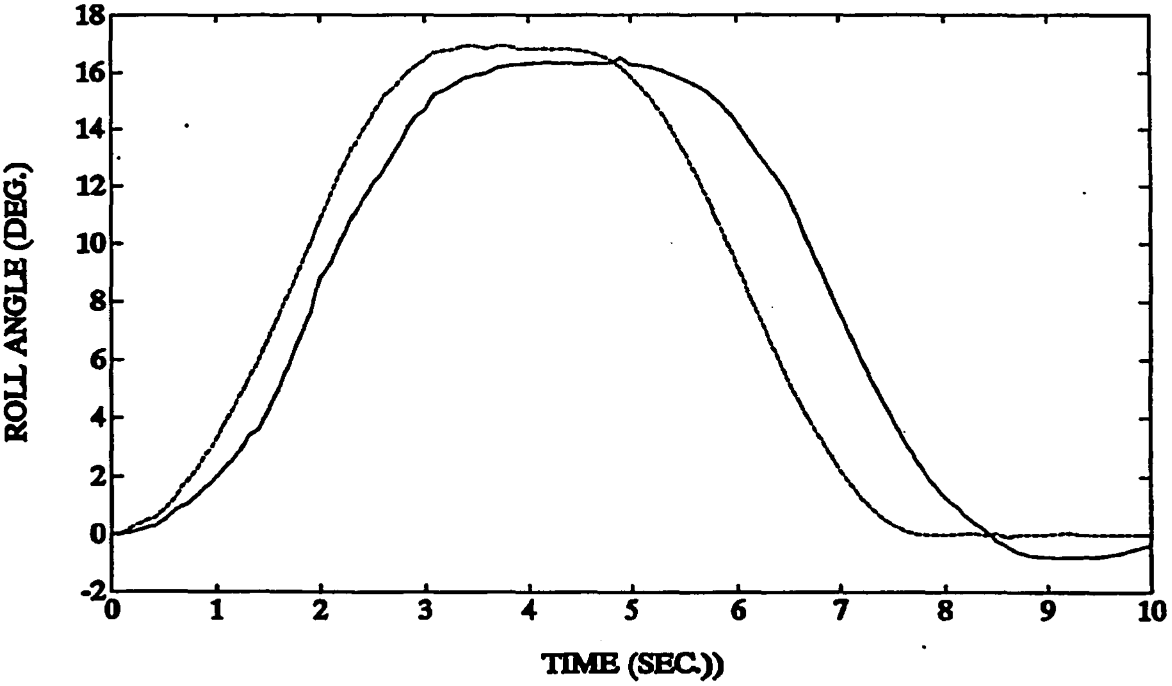
Fig. 15 Comparison of Control During Sink Rate Correction



H-DOT ------------

FACLS__________

Fig. 16 Comparison of Glideslope Control in Turbulence



FACLS ------------

H-DOT__________

Fig. 17 Comparison of Roll Responses During Lineup Correction

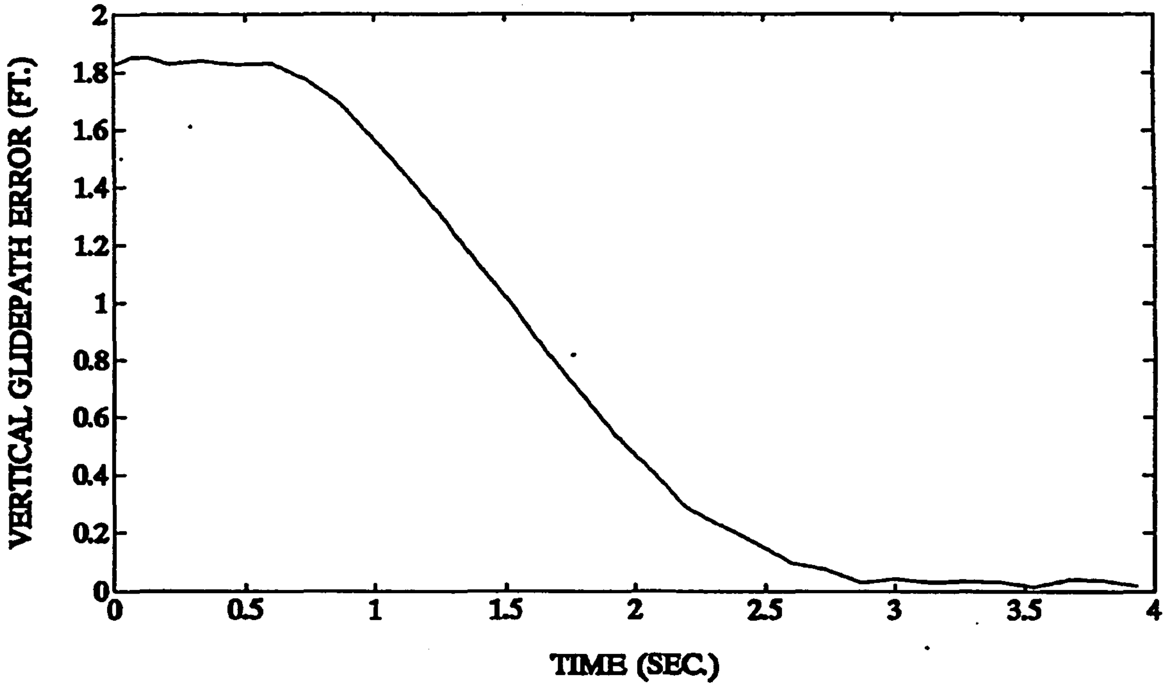


Fig. 18 FACLS Response Before Carrier Air Wake

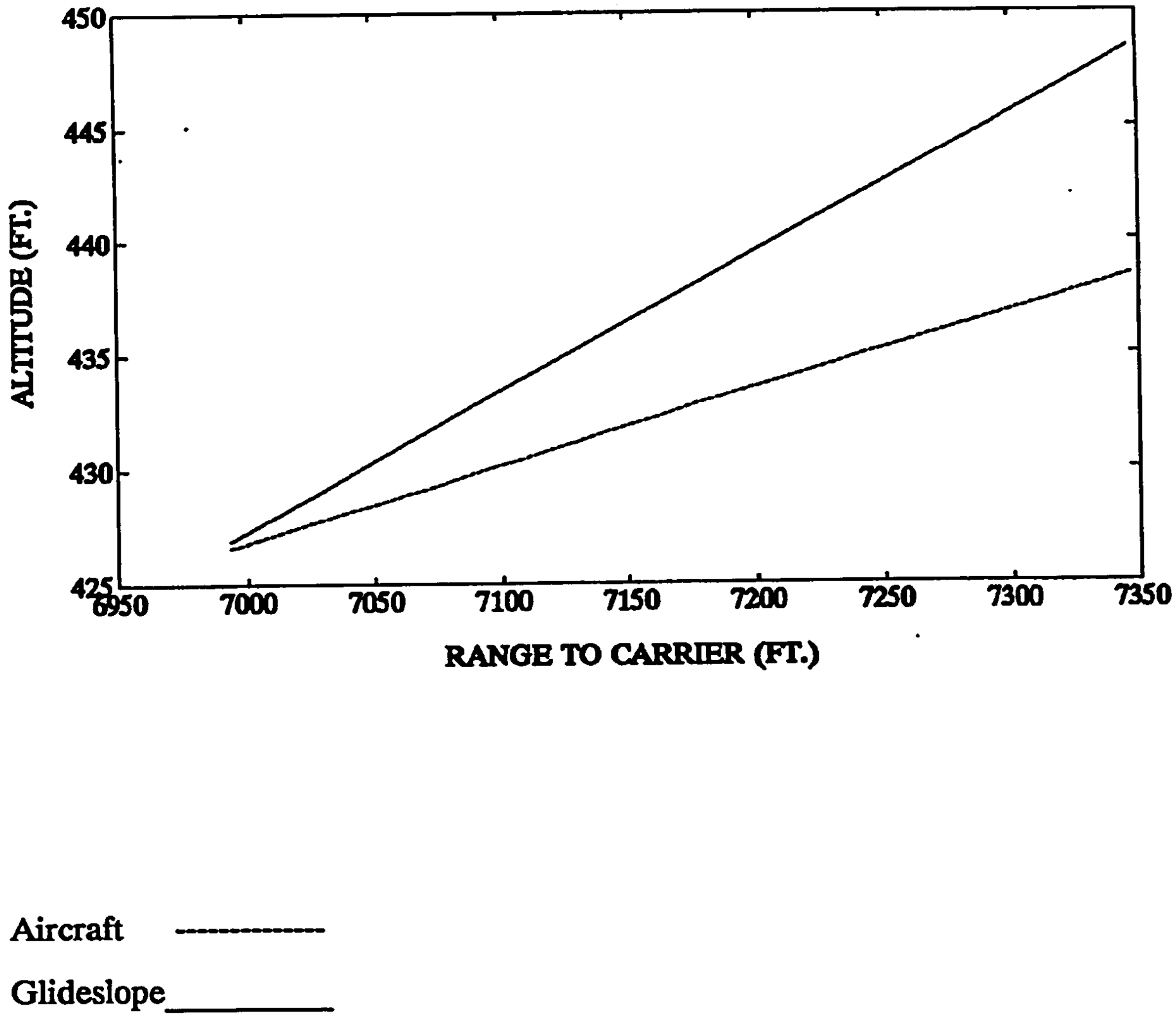


Fig. 19 FACLS Response to Small Decreasing Error at Start

Table 1 Fuzzy Roll Control Rules

Note: Rules 1-19 only apply if range is not at ramp, although this is not written out in each rule.

To simplify this table all lateral stick outputs were classified as small, medium, or large, although there are really 9 values for lateral stick in each direction.

1. If roll error is positive large, then lateral stick is positive large

2. If roll error is positive medium, then lateral stick is postive medium

3. If roll error is positive small, then lateral stick is positive small

Rules 4-6 are identical to 1-3 in the negative direction

7. If roll error is positive medium and roll rate is negative large, then lateral stick is positive large

8. If roll error is positive small and roll rate is negative medium, then lateral stick is positive medium

9. If roll error is positive small and roll rate is negative medium, then lateral stick is postive large

Rules 10-12 are identical to 7-9 in the opposite direction

13. If roll error is near zero and roll rate is zero, then lateral stick is zero.

14. If roll error is near zero and roll rate is positive small, then lateral stick is negative small

15. If roll error is near zero and roll rate is positive medium, then lateral stick is negative medium

16. If roll error is near zero and roll rate is positive large, then lateral stick is negative large

Rules 17-19 are identical to 14-16 in the opposite direction

20. If roll error is small and roll rate is positive large and range is in close, then lateral stick is zero

Rule 21 is identical to rule 20 in the negative direction

22. If range is at ramp, then lateral stick is zero

TABLE 2 FACLS Results Over 200 Carrier Approaches

Each Entry is a comparison with the results for the current F/A-18 ACLS.

Waveoff	48% Reduction
Bolter	21% Increase
Hard Landing	67% Reduction
Ramp Strike	80% Reduction
Excellent	47% Increase
Acceptable	23% Increase
Poor	55% Reduction
Longitudinal Dispersion	23% Reduction in landing short of ideal 4% Increase in landing past ideal
Lateral Dispersion	11% Reduction

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"Potential Role of Neural Networks and Fuzzy Logic in Flight Control Design and Development," AIAA Paper No. 92-0999, 1992.

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