# Fuzzy Logic Control with Genetic Algorithm for the Tiltrotor Aircraft

Chen, Heng, Zuo, Xiaoyang, Zhang, Yuzhou
Northwestern Polytechnical University, Xi'an 710072, People's Republic of China

## Abstract

This paper presents a methodology to synthesize the fuzzy logic controller for flight control of tiltrotor aircraft. The fuzzy rule is based on genetic algorithm that drives a cost function represent tiltrotor aircraft performance and handling characteristics to a minimum. After the FLC parameters are optimized by GA, the controllers such as the rotor panel pitch angle controller and power controller are designed. The results show that the whole system posses the satisfactory performance. This methodology of the fuzzy logic controller design via genetic algorithm is very useful for the engineers.

## Notation

**Symbols**

| | |
|---|---|
| $D$ | drag (lb) |
| $g$ | acceleration of gravity (ft/s$^2$) |
| $h$ | distance in the $\hat{k}$ direction (ft) |
| $i_n$ | nacelle angle (degree) |
| $I_R$ | rotor polar moment of inertial (slugs ft$^2$) |
| $I_Y$ | pitch moment of inertial (slugs ft$^2$) |
| $l$ | distance in the $\hat{i}$ direction (ft) |
| $L$ | lift (lb) |
| $m$ | gross tiltrotor mass |
| $q$ | pitch rate (degree/s) |
| $T$ | thrust from one rotor (lb) |
| $u$ | x component of velocity in body axes (ft/sec) |
| $w$ | z component of velocity in body axes (ft/sec) |
| ↑ | angle of attack (degree) |
| ↓ | rotor panel pitch angle (degree) |
| ↖ | angle of attack (degree) |
| ➔ | pitch angle (degree) |

**Subscripts**

| | |
|---|---|
| $f,F$ | fuselage related |
| $fl$ | flaps |
| $fs$ | free stream |
| $h$ | horizontal flow retardation |
| $hs$, $HS$ | horizontal stabilizer related |
| $I$ | induced flow development |

| | |
|---|---|
| *P* | Power |
| *Ss* | rotor slip stream |
| *T* | thrust |
| *w, W* | wing related |

## Introduction

Tiltrotor aircraft combines the vertical takeoff and landing (VTOL) capability of helicopter with the fast speed cruise performance of turboprop airplanes. Tiltrotor flight compares well to the best aspects of helicopter and airplane flight. The ability to fly both as a helicopter and as an airplane allows tiltrotors to utilize some of the best aspects of both types flight[1~8]. On the other hand, its operation and control become more and more complicate. The study for the longitudinal movement of the tiltrotor aircraft is done and optimal controllers for the takeoff and landing for this aircraft is designed by blending together two artificial intelligence techniques, genetic algorithm and fuzzy control in this paper.

After the longitudinal movement mathematic model of the tiltrotor aircraft has been completed, it states that the changes of rotor panel pitch angle and rotor angles not only can influence the force but also the moments. Because a lot of flight parameters can’t be identified and this airplane’s conversion process is very complicate, the model of the tiltrotor aircraft will have considerable errors and nonlinearity[9] which is difficult to be solved by using the classical theory. In consideration of errors and nonlinearity of the model for tiltrotor aircraft, the Fuzzy Logic Control (FLC) with Genetic Algorithm (GA) is put forward.

Fuzzy Logic Control is not based on the accuracy model of the plant. The theory of fuzzy sets[10,11] becomes a useful instrument for the control engineer as the complexity of the system increases and the ability to understand and predict its behavior in a precise and yet significant manner diminishes. Tuning and optimizing a fuzzy controller is a difficult and a long time task due to the lack of standard procedures.

Genetic algorithms [12,13] (GAs) are parameter search techniques that rely on analogies to natural biological processes. Being global and robust, they have been lately used to solve complex optimization problems in aerospace engineering.

Attempts to blend the two AI techniques have been made in the process of solving problems like fuzzy system identification based on input-output data[14,15,16] and fuzzy controller parameters tuning[17,18].

The tiltrotor aircraft can be controlled by FLC. Meanwhile, A genetic algorithm drives a cost function representing the tiltrotor aircraft performance and handling characteristics to minimum. The cost function is evaluated on_line through simulations performed within the design loop. The genetic algorithm incorporates some novel features to accelerate convergence. After GA is used to optimizing the Fuzzy Logic Control parameters, GA can reduce the huge task of the specialists during designing controller. FLC’s parameters optimizing can completed automatically by programming. The precision and optimization speed are higher.

In this paper, the tiltrotor aircraft flight control system is designed by using the FLC with GA. It is important that the vertical takeoff and landing controllers are designed according to the FLC with GA. A genetic algorithm drives a cost function representing the tiltrotor aircraft performance. The system cost function is evaluated through simulations performed within the design loop. The genetic algorithm incorporates some novel features to accelerate convergence.

After the FLC parameters are optimized in GA, the controllers such as the nacelles angle controller, rotor angle controller and power controller are designed. The results show that the whole system can meet the requirements and posses the satisfactory performance. The good results of simulation for the whole system are obtained. The figures for simulating show that the whole control system possess the perfect performance and demonstrate that the method of design the fuzzy logic controller via genetic algorithm is very useful for the engineers.

## Tiltrotor Aircraft Modeling

To investigate optimal tiltrotor operations, a mathematical model must be used that both adequately describes tiltrotor dynamics and is simple enough to be used efficiently in designing the flight control. A general longitudinal tiltrotor model is introduced in this paper that is suitable for designing purposes.

Studies of tiltrotor aircraft flights have several special challenges compares to those for conventional helicopter[19~21]. In particular, a comprehensive longitudinal tiltrotor model must represent forces and movements produced by the rotors, wing, fuselage and the elevator. In this paper, a two-dimensional rigid body model for tiltrotor aircraft is used[22].

The equations of motion for a tiltrotor aircraft are developed by summing up forces and moments from its individual components, such as rotors, wing, fuselage and horizontal stabilizer. The resulting longitudinal rigid-body equations of motion are listed below.

$$\dot{w} = \frac{A_z}{m} - 2\frac{T}{m}\sin(i_n - \beta) + g\cos\theta + qu$$

(1)

$$\dot{u} = \frac{A_x}{m} + 2\frac{T}{m}\cos(i_n - \beta) - g\sin\theta - qw$$

(2)

$$\dot{\theta} = q$$

(3)

$$\dot{q} = \frac{M_A}{I_{yy}} - \frac{2}{I_{yy}}T[l_R\sin(i_n - \beta) + h_R\cos(i_n - \beta) + d\sin\beta]$$

(4)

$$\dot{h} = u\sin\theta - w\cos\theta$$

(5)

$$\dot{x} = u\cos\theta + w\sin\theta$$

(6)

where g is the acceleration of gravity, $A_z$ and $A_x$ are vertical and horizontal components of aerodynamic forces (respectively) in the body frame, and $M_A$ is the aerodynamic moment about the $y$ axis. $I_{yy}$ is the moment of inertia about the $y$ axis.

$$A_z = -L_f \cos\alpha_f - D_f \sin\alpha_f - L_{w_{fs}} \cos\alpha_{w_{fs}} - D_{w_{fs}} \sin\alpha_{w_{fs}} \\ - L_{w_{ss}} \cos\alpha_{w_{ss}} - D_{w_{ss}} \sin\alpha_{w_{ss}} - L_{hs} \cos\alpha_{hs}$$

(7)

$$A_x = L_f \sin\alpha_f - D_f \cos\alpha_f + L_{w_{fs}} \sin\alpha_{w_{fs}} - Dw_{fs} \cos\alpha_{w_{fs}} \\ + L_{w_{ss}} \sin\alpha_{w_{ss}} - D_{w_{ss}} \cos\alpha_{w_{ss}} + L_{hs} \sin\alpha_{hs}$$

(8)

$$M_A = M_{\alpha_f} - l_F (L_f \cos\alpha_f + D_f \sin\alpha_f) - h_F (L_f \sin\alpha_f - D_f \cos\alpha_f) \\ + M_{\alpha_w} - l_W (L_{w_{fs}} \cos\alpha_{w_{fs}} + D_{w_{fs}} \sin\alpha_{w_{fs}} + L_{w_{ss}} \cos\alpha_{w_{ss}} + D_{w_{ss}} \sin\alpha_{w_{ss}}) \\ - h_W (L_{w_{fs}} \sin\alpha_{w_{fs}} - D_{w_{fs}} \cos\alpha_{w_{fs}} + L_{w_{ss}} \sin\alpha_{w_{ss}} - D_{w_{ss}} \cos\alpha_{w_{ss}}) \\ - l_{HS} L_{hs} \cos\alpha_{hs} - h_{HS} L_{hs} \sin\alpha_{hs}$$

(9)

The control variables of the model are thrust $T$, Nacelle angle $i_n$, Rotor Panel Pitch angle $\beta$.

## Fuzzy Logic Controller

Fuzzy systems theory applied to control of complex processes has emerged, in recent years, as a major alternative to conventional control techniques. The distinguishing features of fuzzy logic, namely, redundancy of an appropriate mathematical model to describe a system[23] and ability to model system of arbitrary nonlinearity[24] to desired accuracy, have facilitated the implementation of fuzzy control over processes that are mathematically intractable or are imprecisely defined. However, in case of processes that are complex but well modeled, the prevailing view in the control-theory community is that fuzzy controllers are easier to establish but fall short of performance good conventional controllers. As will be seen subsequently, the results of the present investigation may render such a viewpoint untenable.

The basic features of the fuzzy logic controller as described as follow. The design of a generic fuzzy system consists of the following sequential steps:

--selecting the process parameters that perform as input and output variables in the fuzzy system.

--the shape of fuzzy membership functions, i.e, Gaussian, triangular, trapezoidal etc.

--the distribution or ‘clustering’ of these membership functions across the domain of definition of each variable.

--the fuzzy inference system, i.e. the rules in the FAM matrix that a combination of input sets to a certain output set and the manner and extent of activation of these rules.

--the defuzzification mechanism that converts fuzzy output to crisp output.

Pitch angle error and angle rate are the inputs of the controllers. The panel pitch angle is the output of the controller.

Parameters of Fuzzy Controller Subject to Optimization:

**1 Membership Function Shape.**

The following symmetric shapes of the membership functions have been considered: trapezoidal, cosine and bell shape. The same shape applies for both the position and velocity inputs as well as for the output of the fuzzy controller.

**2 Scaling factors.**

The usual procedure of normalizing the input and denormalizing the output by means of scaling factors is not used here. The membership functions for the inputs and output of the fuzzy controller are defined on their physical domain. The pitch angle errors and angle rate scaling factors play the role of mapping the domain of the inputs.

**3 The Rules of Fuzzy Logic Control**

The controller performance optimization relates directly to selection of rules in FAM matrix.

## Genetic Algorithm

Genetic Algorithms (GA) is exploratory search and optimization procedures that are based on the principles of biological evolution. The ‘survival of the fittest’ dictum is allowed to drive the parameters of physical process to the state that produces optimal or ‘fittest’ value of a ‘fitness function’. The basic features of a GA that distinguishes it from other optimization techniques such as gradient descent methods are the following:

-- GA work on a coding of the parameters to be optimized, rather than the parameters themselves. Binary and decimal coding is often, though not always used.

-- GA use an objective assessment, through a fitness function, of a solution vector to guide the search of the problem space.

-- GA use probabilistic rules to make choices in their operation.

-- GA search a space using a population of possible solution vectors. The initial population is randomly generated. By dealing with several independent solution points, the GA samples the search space in parallel and is hence much less susceptible to getting trapped in suboptimal solutions.

There are three well defined operations in a GA procedure – selection, crossover and mutation. Starting with a population of strings representing codified solution vectors from the total solution space, selection creates a new generation of population by randomly selecting string from the current generation, with weightage given to the fitness value of each sting. Strings with higher fitness are likely to get more copies in the new generation, and those with low fitness might be eliminated, the word ‘might’ signifying the probabilistic nature of the GA. Crossover takes up pairs of strings and switches the bits lying on one side of a particular common ‘crossover point’. Mutation flips individual bits of a setting once in a while based on a probability of mutation. The operation of crossover leads to creation of new solutions, while mutation allows the solution to jump from one point of the solution space to another. Together, all three operations complementarily guide the GA process towards the optimal solution with highest fitness.

In this fuzzy rule base optimization problem, decimal coding is used to express each rule as a solution for the problem. A population of initial member strings thus designed, is operated upon by the three fundamental GA operations – selection, crossover and mutation – advancing its evolution towards optimal solution. It is, however, the experience of most GA applications for multi-dimensional optimization problems that, once the solution enters the small ‘fuzzy’ subdomain of the total solution space lying in the close neighborhood of the global optimum, it converges extremely slowly and may even tend to stagnate. Hence certain acceleration techniques have to be introduced in the basic GA procedure to obtain the optimal solution.

## Controller design implementation

The tiltrotor aircraft that tends to trade stability for high maneuverability rely heavily on the high quality control. The tiltrotor aircraft control system has to be designed to ensure static and dynamic stability while providing satisfactory handling qualities. Further, increasing requirements on the tiltrotor aircraft for performing large maneuvers within an expanding flight envelope introduce uncertainties in the tiltrotor aircraft control. One, possibly cost and time effective, approach for such a design is to bring to bear emerging computational intelligence techniques that have so far found significant application in no-flight control sectors. These include fuzzy logic (FL), genetic algorithm (GA) and neural network based techniques.

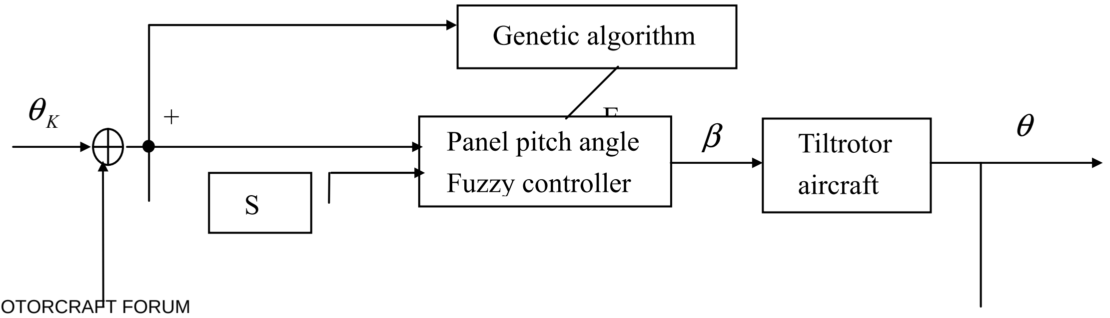
Complex maneuvers of the tiltrotor aircraft involving large incidences induce significant nonlinearities in aircraft dynamics. These are mathematically difficult to model and complicate the task of developing conventional controllers. Fuzzy logic control via GA, with its implicit encapsulation of nonlinearities and redundancy in need for mathematical models, appears naturally advantageous in these regions.

**1 Construction of Fuzzy Logic Controller with GA.**

The command to the controlled system is the desired pitch angle of the tiltrotor aircraft. The whole fuzzy logic control system with GA is showed in Figure 1. Therefore, pitch angle error and pitch rate error $\Delta\theta$ and $\Delta\dot{\theta}$ are evaluated and used to generate the inputs to the controller. The panel pitch angle↓is the output of the controller. Fuzzy variables $E\theta$ and $E\dot{\theta}$ are divided into six language value: NB, NM, NS, Z,PS, PM, and PB, and the universe of discourse is classified to 15 degree: -7, -6, -5, -4, -3, -2, -1, 0, 1, 2, 3, 4, 5, 6, 7. The domain of the inputs and output of the controller and fuzzy rule are need to optimized by the GA.

The rule optimization procedure consists of the following steps[25].

step 1 Select the population
step 2 Generate the new generation by using operations crossover and mutation
step 3 Domain of the fuzzy variables program into the string
step 4 Calculate the fitness function
step 5 Select the fittest body, then generate new generation population
step 6 If find the best result, optimization is over
step 7 Go to step2



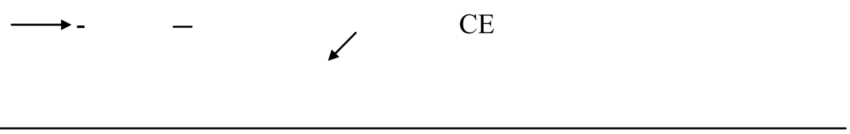


Figure 1 Construction of the control system

**2. Coding string.**

The decimal coding string is used in this paper. The optimizing parameters are the domains of two inputs and one output of the fuzzy logic controller and control value. The string is consisted of the first decimal inputs domain value part and second output part (shown as table1,2). The decimal string represents the 4 inputs values and 225 output values. In this case, the high optimization effect will be obtained. :

Table1 inputs domain values

| | | | |
|---|---|---|---|
| $a_e$ | $b_e$ | $a_{ce}$ | $b_{ce}$ |

Table2 output values

| | | | | | | |
|---|---|---|---|---|---|---|
| $u_{1,1}$ | $U_{1,2}$ | | $u_{2,1}$ | $u_{2,2}$ | …… | $u_{15,15}$ |

**3 To select the fitness function.**

The fitness function is very important for the whole system. At first, the cost function is selected on the requirements of the tiltrotor aircraft flight control.

$$f = \alpha \cdot \frac{\sigma_m - \sigma}{\sigma_m} + \beta \cdot \frac{t_{sm} - t_s}{t_{sm}} + \gamma \cdot \frac{e_m - e_s}{e_m}$$

(10)

In the above formula(10), $\sigma$ is the overshoot, $t_s$ is the settling time for the whole control system, $e$ is the stable error, $\alpha, \beta, \gamma$ are the weight value for these characters volume. After adjusting the weight value, the performance of the system can be obtained.

Then the fitness function $f_{si}$ is designed as formula (11).

$$f_{Si} = \frac{f_i}{\sum_{j=1}^{n} f_j}$$

(11)

Meanwhile the selection crossover and mutation will be used to produce the new generation population.

## Results

Design the controller for the tiltrotor aircraft:

1) Vertical takeoff:

When the tiltrotor aircraft takeoffs vertically, nacelle is fixed 90 degrees position. The power of the engine is max. By controlling panel pitch angle, the aircraft pitch angle will be adjusted. After aircraft takeoff over 400 fts, the vertical takeoff is over. Then the tiltrotor aircraft begins the conversion procedure. During the takeoff procedure the attitudes angle is very important for the tiltrotor aircraft. Controlling the attitudes angle is main task during the takeoff procedure.

Variables can be show as follow: $T = T_{max}$, $i_n = 90^o$, $\theta = 10^o$, $h = 400$ft. Control variable is prorotor pitch angle $\beta$.

The population size is selected 40. Firstly the variables are produced randomly such which are $a_e$, $b_e$, $a_{ce}$, $b_{ce}$ . Then the function has to be selected in the domain of the inputs and outputs.

After derived more than 95 generations, the following variables will obtained□weight variables:$\alpha=0.1$□$\beta=0.45$□$\gamma=0.45$□at this situation the optimization parameters as follow.

Table 5 Domain of the inputs:

| $a_e$ | $b_e$ | $a_{ce}$ | $b_{ce}$ |
|---|---|---|---|
| -8.599 | 8.599 | -5.90 | 5.90 |

Meanwhile the fuzzy controller rules can be obtained by GA parameters optimizing.

The table 6 is the error and cost function changed state. As the generation number is increasing, the error value and cost function value become smaller and smaller.

Table 6

| Generation No | Error value | Cost function value |
|---|---|---|
| 1 | 4.0105 | 0.14951 |
| 5 | 3.9010 | 0.14625 |
| 10 | 3.8404 | 0.14432 |
| 15 | 3.8913 | 0.14116 |
| 20 | 3.5480 | 0.14102 |
| 25 | 3.4349 | 0.12986 |
| 30 | 3.2916 | 0.12839 |
| 35 | 3.3246 | 0.11970 |
| 40 | 3.1041 | 0.11687 |
| 45 | 2.9523 | 0.10540 |
| 50 | 2.6595 | 0.10459 |
| 55 | 2.5806 | 0.09161 |
| 60 | 2.4005 | 0.07839 |
| 65 | 2.2153 | 0.07490 |

| | | |
|---|---|---|
| 70 | 2.2699 | 0.07274 |
| 75 | 2.0369 | 0.07240 |
| 80 | 1.9387 | 0.05971 |
| 85 | 1.8392 | 0.05949 |
| 90 | 1.7679 | 0.05875 |

Figure 2 shows that the whole control system posses the good performance. After a short time adjusting, the pitch angle can rapidly keep the target value.

2) Conversion

During conversion procedure, control variables include the elevator and pitch angle to control the tiltrotor aircraft attitudes angles. The former design method for the takeoff procedure is used to design the controllers of the elevator and pitch angle. Finally, the controllers can be obtained. The good performance demonstrates that the fuzzy logic controller via genetic algorithm is very effective and easy to design for the engineers.

3) Landing

Similar with the above takeoff, the controller for tiltrotor aircraft landing can be design by using the fuzzy logic control via genetic algorithm. In figure 4, the performance of landing showed. Initially, the speed is higher, so the elevator is adjusted to keep the pitch angle constant. As the speed decreasing, power controller is more important. Finally, the pitch angle can keep a little constant angle.

## Conclusion

This paper has investigated designing the controllers for the tiltrotor aircraft takeoff, conversion and landing procedures. A longitudinal rigid body tiltrotor model was introduced. For solving the nonliearity of tiltrotor aircraft, the fuzzy logic control is used to design the controllers for tiltrotor aircraft. The fuzzy rules and inputs domain parameters are optimized based on Genetic Algorithm. The figures for simulating show that the whole control system possess the perfect performance and demonstrate that the method of design the fuzzy logic controller via genetic algorithm is very useful for the engineers.

## References

1 Maisel, M.D., “Tilt Rotor Research Familiarization Document”, NASA TM X-62, 407, January 1975

2 Durgan, D.C., Erhart, R.G. and Schroers, L.G., “The XV-15 Tilt Rotor Research Aircraft,” NASA TM 81244, Sept. 1980

3 Churchill, G.B., and Dugan, D.C., “Simulation of the XV-15 Tilt Rotor Research Aircraft,” NASA 84222, March, 1982.

4 Marr, R.L., Willis, J.M., and Churchill, G.B., “Flight Control System Development for the XV-15 Tilt Rotor Aircraft, ” Presented at the 32nd Annual National V/STOL Forum of the American Helicopter Society, May 1976

5 Marr, R.L., “Wind Tunnel Test Results of 25-Foot Tilt Rotor During Autorotation,” NASA CR 137824, February 1976

6 Marr, R.L., “Final Report, XV-15 Flight Simulation Period No. 2 (FSAA Simulator July 1974),” BHC Report No. 81-RLM: seb-174, August 30, 1974

7 Fletcher, K.S., Decker, W.A., Matuska, D.G., Moris, P.M., and Smith, M.T. “VMS Simulation of a Variable Diameter Tiltrotor,” Presented at the 53rd Annual National Forum of the American Helicopter Society, April 1997

8 Wernicke, K.C., “Performance and Safety Aspects of the XV-15 Tilt Rotor Research Aircraft,” Presented at the 33rd Annual National Forum of the American Helicopter Society, May 1977

9 Eric B. Carlson, Yiyuan Zhao, Robert T. N. Chen, “Optimal Tiltrotor Runway Operations in One Engine Inoperative”, AIAA-99-3961

10. Driankov D., et al., “An Introduction to Fuzzy Control ,” Springer Verlag, 1993

11. Pedryca W., “Fuzzy Control and Fuzzy Systems, ” John Wiley&Sons Inc., 1993

12. Michalewicz, Z., “Genetic Algorithm + Data Structure = Evolution Programs,” Springer Verlog, 1994

13. Davis, L., “Handbook of Genetic Algorithm,” Van Nostrand Reinhold, New York, 1991

14. Park D., Kandel A., Langholz G., “Genetic Based New Fuzzy Reasoning Method with Applications to Fuzzy Control,” IEE Trans. On SMC, vol.24 no.1 1994

15. Giuclea M., Agapie A., Fagarasan F., “A GA Approach for Closed-Loop System Identification,” Proc. of EUFIT’96, Aachen, Germany, 1996

16 Negoita M., Gh.,,Agapie A., Fagarasan F., “Applications of Genetic Algorithms in solving Fuzzy Relational Equations,” Proc. of EUFIT’94 Aachen, Germany, 1994

17. Ng K. C., Li Y., “Design of Sophisticated Fuzzy Logic Controllers Using Genetic Algorithms,” Proc. of the 3rd IEEE Int. Conf on Fuzzy Systems, 1994

18. Li Y., Ng K. C., “Genetic Algorithm Based Techniques for Design Automation of Three-term Fuzzy Systems,” Proc. of the 6th Int. Conf. of the Fuzzy System Association, Sao Paolo, Brazil, 1995

19. Johnson, W., “Helicopter Optimal Descent and Landing After Power Loss,” NASA TM 73244, May 1977

20. Lee, A. Y., Bryson, A. E., and Hindson, W. S., “Optimal Landing of a Helicopter in Autorotation,” Journal of Guidance, Control, and Dynamics, Vol. 11, No. 1, Jan.-Feb., 1988, pp.7-12

21 Okuno, Y., Kawachi, K., Azuma, A., and Saito, A. “Analytical Prediction of Height-Velocity Diagram of a Helicopter Using Optimal Control Theory,” Journal of Guidance, Control, and Dynamics, Vol. 14, No. 2, March-April, 1991, pp. 453-459

22 Eric B. Carlson, Yiyuan, Zhao, Robert T. N. Chen “Optimal Tiltrotor Runway Operations in One Engine Inoperative” AIAA-99-3961

23 B. Kosko, Neural Networks and Fuzzy System, Englewood Cliffs, NJ: Prentice Hall, 1992

24 Li Xin, Wang, Adaptive Fuzzy Systems and Control-Design and Stability Analysis, Englewood, Cliffs, NJ: Prentice Hall, 1994

25 Coza, John, R.. Genetic Programming: On the Programming of Computers by Means of Natural Selection\. Cambridge, Mass.: MIT press, 1992, 94--96

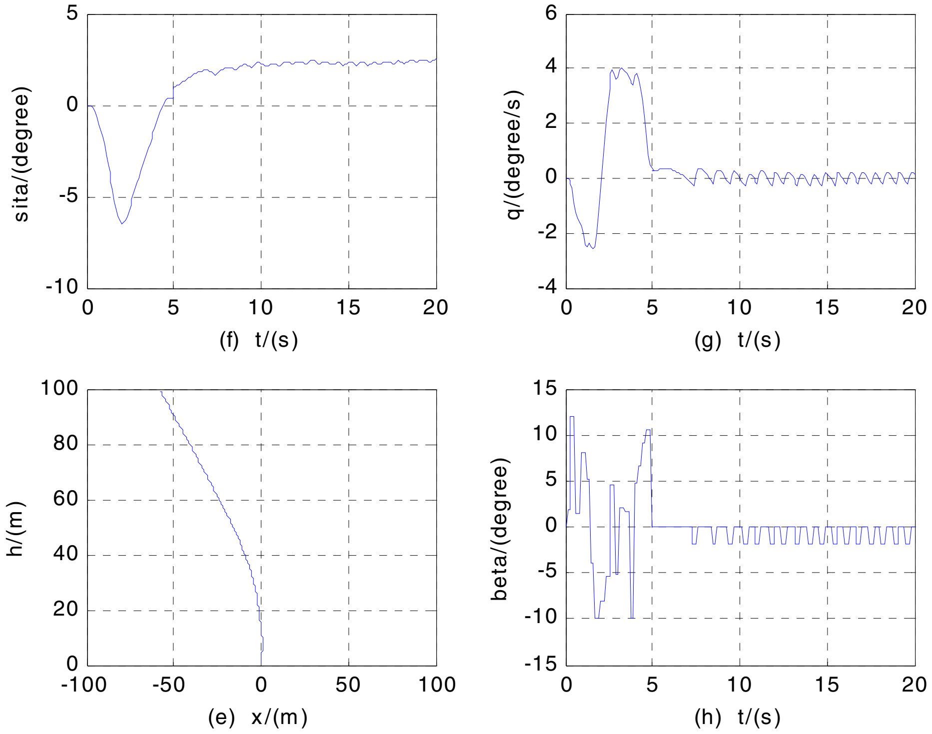


figure 2 Vertical Takeoff Performance

(sita: pitch angle, q: pitch rate, beta: panel pitch angle, h:height, x: forward distances )

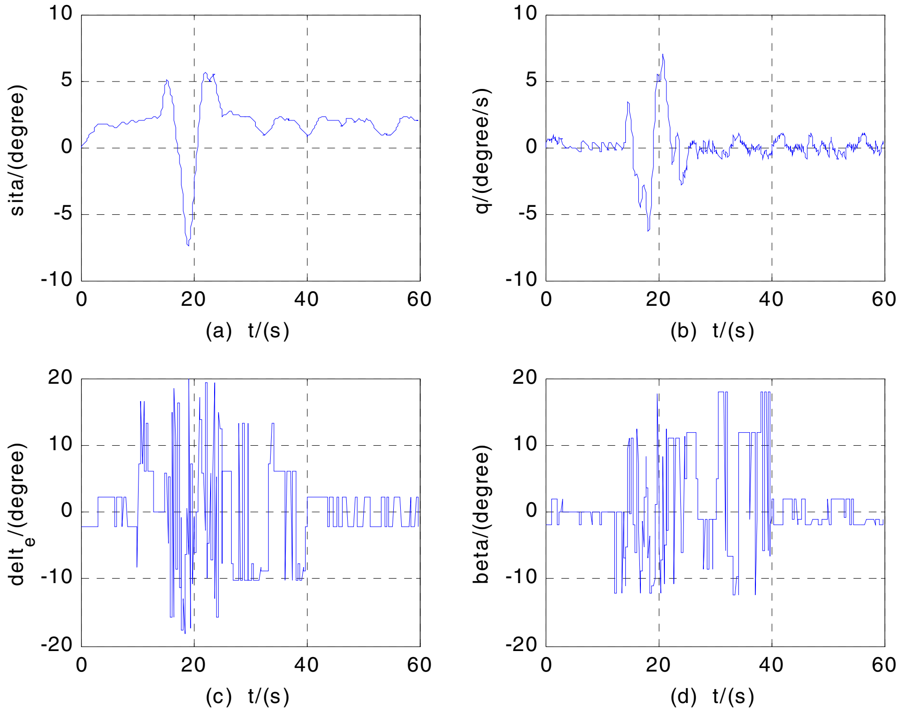


figure 3 Conversion Process Performance

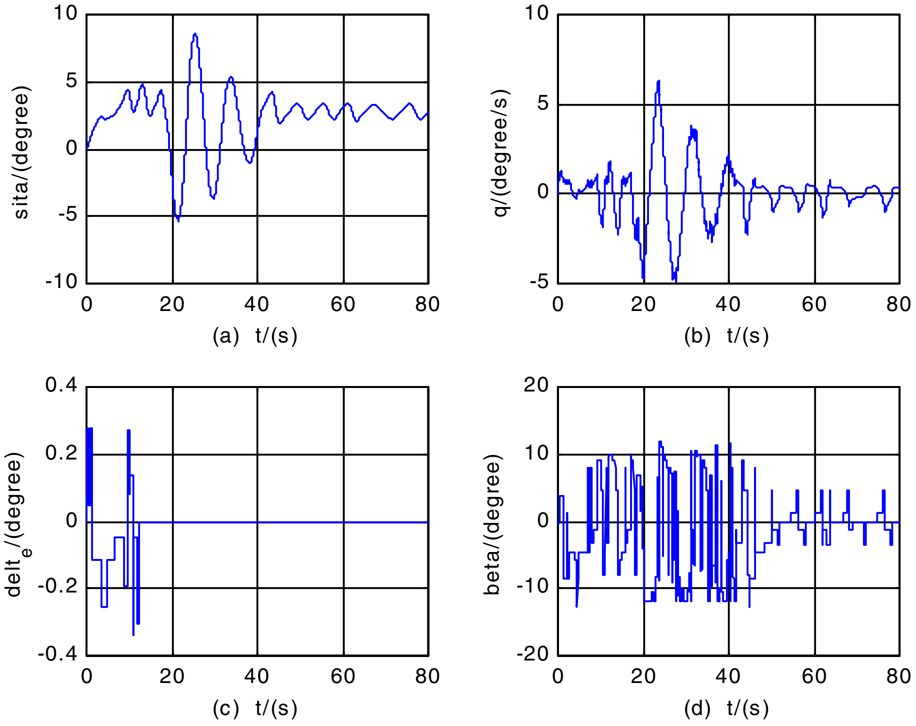


figure 4 Landing Period Performance