DEVELOPMENT OF FUZZY LOGIC LQR CONTROL INTEGRATION FOR AERIAL REFUELING AUTOPILOT

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ABSTRACT

This paper investigates the performance on the aircraft control system during air refuel purposes of the Linear Quadratic Regulator (LQR) control alone, and the integration between fuzzy control and LQR. LQR is modern linear control that is suitable for multivariable state feedback and is known to yield good performance for linear systems or for nonlinear systems where the nonlinear aspects are presented. The fuzzy control is known to have the ability to deal with nonlinearities without having to use advanced mathematics. The LQR integrated fuzzy control (LQRIFC) simultaneously makes use of the good performance of the LQR in the region close to switching curve, and the effectiveness of the fuzzy control in region away from switching curve. A new analysis of the fuzzy system behavior presented helps to make possible precise integration of LQR features into the fuzzy control. The LQRIFC is verified by simulation to suppress the uncertainty instability more effectively than the LQR besides minimizing the time of the mission proposed.

KEY WORDS

Fuzzy control, LQR, Aerial refueling, Autopilot

NOMENCLATURE

(LQR) linear quadratic regulator, (FLC) fuzzy logic controller, (COA) central of area, (FOS) fuzzy net output signal

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1. INTRODUCTION

The objective of the present work is to minimize the net performance index (PI) of the aircraft control system during aerial refueling process by using fuzzy logic LQR control integration instead of using LQR alone. Effectiveness of this method is mostly appeared when the system is highly nonlinear and exposed to surrounding uncertainty. Using of such integration permit stability and robustness of the system specially when applying different optimization methods for fuzzy logic parameters tuning.

2. AIRCRAFT MODELING

One of the key phases in aircraft design is the knowledge acquisition about the aerodynamic data that can be used in all the computer oriented design approaches, using this data the designer can build up a simulated nonlinear model for this aircraft. For our research we had used flight aerodynamic data given by (Brumbaugh, 1991) and (Stevens & Lewis, 1992) [1]. The employed flight model is a stability axis model, with a state vector $[\alpha\ q\ \delta_e\ \alpha_f]$ for pitch rate control and $[\beta\ \varphi\ p\ r\ \delta_a\ \delta_r]$ for lateral control.

3. OPTIMAL FLIGHT CONTROL (LQR)

The modern control system design is based directly on the state variable model, which contains more information about the system. Another central concept is the expression of performance specifications in terms of a mathematically precise performance criterion that then yields matrix equations for the control gains. The classical successive loop closure approach means that the control gains are selected individually. In contrast, solving matrix equations in modern control allows all the control gains to be computed simultaneously so that all the loops are closed at the same time with stable closed loop poles (as an algorithm condition). This could be achieved by selecting the control input $u(t)$ to minimize a quadratic cost or performance index (PI) of the type

$$J = \frac{1}{2}\int_0^\infty (\tilde{x}^T Q \tilde{x} + \tilde{u}^T R \tilde{u}) + \frac{1}{2}\tilde{e}^T V \tilde{e}\ dt \tag{1}$$

Where Q and R are symmetric positive semi-definite weighting matrices, $\tilde{x}$, $\tilde{u}$, $\tilde{e}$ are state, control, steady state error respectively

4. APPLYING FUZZY INFERENCE SYSTEM FOR CONTROL

The fuzzy inference technique can be very useful in control engineering. A standard control system would utilize a numerical input and produce numerical output and so should a fuzzy controller. The knowledge base contains the set of inference rules chosen to achieve the control objectives and the parameters of the fuzzy systems used to define the data manipulation in the fuzzification, inference engine, and defuzzification processes as shown in Fig. 1. Input to the fuzzification process is the measured or estimated variable that appears in the antecedent part of the if-then rule. This input variable has associated linguistic values to describe it. Each linguistic value is defined by a membership function, parameterized by data from the knowledge base .In the inference engine the decision–making logic is conducted, inferring control laws from the input variables through fuzzy implication. The final step is the defuzzification process where a crisp control command is determined based on the inferred fuzzy control law.

4.1 Structure of Fuzzy Rules

A fuzzy rule is the basic unit for capturing knowledge in many fuzzy systems. A fuzzy rule has two components: an if-part (also referred to as the antecedent) and a then-rule (also referred to as the consequent):

IF <antecedent> THEN <consequent>

The antecedent describes a condition, and the consequent describes a conclusion that can be drawn when the condition holds.

The structure of a fuzzy rule is identical to that of a conventional rule in artificial intelligence. The main difference lies in the content of the rule antecedent. The antecedent of the fuzzy describes an elastic condition (a condition that can be satisfied to a degree) while the antecedent of a conventional rule describes a rigid condition (a condition that is either satisfied or dissatisfied)[2].

4.2 Rule Derivation

Motivated by the need of a systematic method to generate and modify fuzzy rule-bases, much research is being conducted on developing learning approaches. This technique begins with the self-organizing controllers which consist of two levels of fuzzy rule bases. The first rule base is the standard control fuzzy rule

base. The second level contains a fuzzy rule base consisting of meta-rules, which attempt to assess the performance of the close loop control system and subsequently used to modify the standard rule base. Learning approaches based on evaluation theory, such as genetic algorithms[3], have a promising potential towards the derivation of fuzzy rule bases as done in this work. Fig. 2 shows one sort of the speed controllers that have been used utilizing both control signals (error and error rate) according to the line of sight distance between the aircraft and the tanker, tuning the normalized and the denormalized factors along different operating points simulating the gain scheduling technique for the LQR control. The result of applying COA defuzzification to a fuzzy conclusion can be expressed by the formula:

$$y = \frac{\sum_i \mu_A(y_i) \times y_i}{\sum_i \mu_A(y_i)} \tag{2}$$

where μ_A is the membership of area A.

In the same manner nonlinear PID fuzzy logic controller was proposed to be integrated with LQR controller (inner loop) for both pitch and lateral control purposes as an outer loop control. Fig. 3 shows the different output control gains after performing the (COA) defuzzification process for Mamdani type 49 rule base PID nonlinear fuzzy logic controller (7X7 membership functions). The following rules describe the logic behavior of the PID nonlinear controller as an example, in the same way it possible to deduce the rule-base for the speed controller.

1. if (e is NB) and (ec is NB) then (kp is PB)(Ki is NB)(Kd is PS)(1)
    :   :   :   :   :   :   :   :   :   :
49. if (e is PB) and (ec is PB) then (kp is NB)(Ki is PB)(Kd is PB)(1)

5. THE LQR INTEGRATED FUZZY CONTROL (LQRIFC)

The LQR integrated fuzzy control utilizes both advantages from the LQR controller and fuzzy logic controller as LQR controller can easily satisfies the flying qualities and pilot rating requirements and fuzzy control can cope with the nonlinearity of the system introducing a smart way to modifying the output gains according to the actual performance blending the dynamic response that generating better performance than using LQR alone. Fig. 4 describes the LQR integrated fuzzy control (LQRIFC) for pitch controller. The system dynamics is evaluated by LQR design process at each trimmed point for pitch control, in the

same manner it is possible to introduce the same procedure for lateral-directional control Fig. 5. Eventually the LQR closed loop system poles can easily satisfy the flying qualities specifications such as the damping ratio and the natural frequencies which is the main requirement in designing closed loop aircraft control system [4].

The states and output of the plant plus the compensator for both pitch and lateral motions are

$$x_{pitch} = \begin{bmatrix} \alpha & q & \delta_e & \alpha_F & \varepsilon \end{bmatrix}^T, \ y_{pitch} = \begin{bmatrix} \alpha_F & q & \varepsilon \end{bmatrix}^T$$

$$x_{lateral} = \begin{bmatrix} \beta & \phi & p & r & \delta_a & \delta_r & x_w & \varepsilon \end{bmatrix}^T, \ y_{lateral} = \begin{bmatrix} \varepsilon & e_r & p & e_\phi \end{bmatrix}^T$$

$$x^\bullet = Ax + Bu + Gr \tag{3}$$

$$y = Cx + Fr \tag{4}$$

$$Z = Hx \tag{5}$$

$$u = -Ky \tag{6}$$

$$A = \begin{bmatrix} \tilde{A}_{\alpha\alpha} & \tilde{A}_{\alpha q} & \tilde{B}_{\alpha\delta e} & 0 & 0 \\ \tilde{A}_{q\alpha} & \tilde{A}_{qq} & \tilde{B}_{q\delta e} & 0 & 0 \\ 0 & 0 & -20.2 & 0 & 0 \\ 10.0 & 0 & 0 & -10 & 0 \\ 0 & -57.2958 & 0 & 0 & 0 \end{bmatrix}, B = \begin{bmatrix} 0 \\ 0 \\ 20.2 \\ 0 \\ 0 \end{bmatrix}, G = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 1 \end{bmatrix}, F = \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix}$$

$$C = \begin{bmatrix} 0 & 0 & 0 & 57.2958 & 0 \\ 0 & 57.2958 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix}, H = \begin{bmatrix} 0 & 57.2958 & 0 & 0 & 0 \end{bmatrix}, u = -Ky = -\begin{bmatrix} K_\alpha & K_q & K_I \end{bmatrix}$$

$$A = \begin{bmatrix} \tilde{A}_{\beta\beta} & \tilde{A}_{\phi\beta} & \tilde{A}_{p\beta} & \tilde{A}_{r\beta} & \tilde{B}_{\delta a\beta} & \tilde{B}_{\delta r\beta} & 0 & 0 \\ \tilde{A}_{\beta\phi} & \tilde{A}_{\phi\phi} & \tilde{A}_{p\phi} & \tilde{A}_{r\phi} & \tilde{B}_{\delta a\phi} & \tilde{B}_{\delta r\phi} & 0 & 0 \\ \tilde{A}_{\beta p} & \tilde{A}_{qp} & \tilde{A}_{pp} & \tilde{A}_{rp} & \tilde{B}_{\delta a p} & \tilde{B}_{\delta r p} & 0 & 0 \\ \tilde{A}_{\beta r} & \tilde{A}_{\phi r} & \tilde{A}_{pr} & \tilde{A}_{rr} & \tilde{B}_{\delta a r} & \tilde{B}_{\delta r r} & 0 & 0 \\ 0 & 0 & 0 & 0 & -20.2 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & -20.2 & 0 & 0 \\ 0 & 0 & 0 & 57.2958 & 0 & 0 & -1 & 0 \\ 0 & -1 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}, B = \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 20.2 & 0 \\ 0 & 20.2 \\ 0 & 0 \\ 0 & 0 \end{bmatrix}, G = \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 1 & 0 \end{bmatrix}$$

$$z = \begin{bmatrix} \varphi \\ r_w \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 57.2958 & 0 & 0 & -1 & 0 \end{bmatrix} x = Hx$$

$$y = \begin{bmatrix} \in \\ e_r \\ p \\ e_\varphi \end{bmatrix} = Cx + Fr_c \quad C = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & -57.2958 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} \quad F = \begin{bmatrix} 0 & 0 \\ 0 & 1 \\ 0 & 0 \\ 1 & 0 \end{bmatrix}$$

The control input $u = \begin{bmatrix} u_a & u_r \end{bmatrix}^T$ may be expressed as $u = -Ky$

with $K = \begin{bmatrix} k_1 & 0 & k_3 & k_4 \\ 0 & k_2 & 0 & 0 \end{bmatrix}$

6. APPLICATION METHODOLOGY FOR AERIAL REFUELING INTEGRATED CONTROL SYSTEM

The refueling procedure requires the tanker to fly straight and level at a constant velocity. The receiving aircraft then closes in and moves to a standard position behind and below the tanker boom. The two aircraft continue to fly in this formation while the boom operator in the tanker's tail uses a joystick to move the boom into position just above the receiver of the plane to be refueled. The operator then extends the telescoping component of the main boom until the nozzle is inserted into the receiver. This can be done automatically using some kind of autopilot consists of three controllers one for pitch control, the second for lateral control and the third for controlling the aircraft speed. Both controllers proposed for pitch and lateral control will apply the LQR fuzzy control integration and the other speed controller uses only fuzzy logic controller 14 rule-base Mamdani type. The input references for both pitch and lateral controllers will be fed by the tanker location on the head up display inside the cockpit. The input reference for the speed controllers will be fed by the line of sight distance between the aircraft and the tanker. For simulation purposes it is required to map the tanker position from the earth fixed frame of reference to the aircraft wing coordinates and this can be done by the proposed transformation as shown in Fig. 6. Implementing the whole integrated aircraft control system on MATLAB/ SIMULINK thus calculating the actual trajectories and relative distance between the aircraft and the tanker as shown in Fig. 7. Practically the relative distances can be calculated by the Head Up display or GPS information that mounted on both tanker and the aircraft connected to each other through UHF channels .

The following equations explain the transformation procedure starting from the tanker position with respect to fixed frame of reference to wing coordinate of the receiving aircraft with initializing small perturbed step (0.0001) to avoid the singularities during simulation calculation.

X   =   Tanker X component relative to the fixed frame of reference

Y   = Tanker Y component relative to the fixed frame of reference
Z   = Tanker Z component relative to the fixed frame of reference
X_F = Fighter X component relative to the fixed frame of reference
Y_F = Fighter Y component relative to the fixed frame of reference
Z_F = Fighter Z component relative to the fixed frame of reference
X_{BO} = Tanker X component relative to aircraft body axes at the fixed frame of reference
Y_{BO} = Tanker Y component relative to aircraft body axes at the fixed frame of reference
Z_{BO} = Tanker Z component relative to aircraft body axes at the fixed frame of reference
X_B = Tanker X component relative to aircraft body axes
Y_B = Tanker Y component relative to aircraft body axes
Z_B = Tanker Z component relative to aircraft body axes
θ, Φ, ψ = Rotation around X,Y, Z axes

$A = \cos\theta \cos\psi$
$B = (\sin\Phi \sin\theta \cos\psi - \cos\Phi \sin\psi)$
$C = (\cos\Phi \sin\theta \cos\psi + \sin\Phi \sin\psi)$
$D = \cos\theta \sin\psi$
$E = (\sin\Phi \sin\theta \sin\psi + \cos\Phi \cos\psi)$
$F = (\cos\Phi \sin\theta \sin\psi - \sin\Phi \cos\psi)$
$G = -\sin\theta$
$M = \sin\Phi \cos\theta$
$N = \cos\Phi \cos\theta$

$$Z_{BO} = \frac{[(YA - XD)(BG - MA) - (XG - ZA)(EA - BD)]}{[(FA - CD)(BG - MA) - (CG - NA)(EA - BD)]} \tag{7}$$

$$Y_{BO} = \frac{[(YA - XD) - Z_{BO}(FA - CD)]}{(EA - BD)} \tag{8}$$

$$X_{BO} = \frac{(X - Y_{BO}B - Z_{BO}C)}{A} \tag{9}$$

$$Z_{SHIFT} = \frac{[(Y_F A - X_F D)(BG - MA) - (X_F G - Z_F A)(EA - BD)]}{[(FA - CD)(BG - MA) - (CG - NA)(EA - BD)]} \tag{10}$$

$$Y_{SHIFT} = \frac{[(Y_F A - X_F D) - Z_{SHIFT}(FA - CD)]}{(EA - BD)} \tag{11}$$

$$X_{SHIFT} = \frac{(X_F - Y_{SHIFT}B - Z_{SHIFT}C)}{A} \tag{12}$$

$X_B = X_{BO} - X_{shift}$ (13)
$Y_B = Y_{BO} - Y_{shift}$ (14)
$Z_B = Z_{BO} - Z_{shift}$ (15)

Fig. 8 shows all the control efforts of the control surfaces and the aircraft engine power during the whole mission starting from the start point as in Fig. 7. until to

the point of contact to the tanker which is the most essential interval in the mission. The alignment terminal control secures the position of the receiving aircraft beneath the tanker of about 30 (ft) and the steady flight speed is equal the same as the tanker flight speed. The figures show also the relative speed and distances between the receiving aircraft and the tanker.

7. CONCLUSION

It is clear that designing aircraft controllers using the integration of both fuzzy logic and LQR has a great benefit in tuning the output performance of the aircraft particularly in aerial refueling systems. As the designing such autopilot requires high precision in controlling the receiving aircraft to a certain lower point under the flying tankers. The control strategy used will be divided into 3 phases, first phase is the stability system augmentation stabilizing the receiving aircraft at initial steady state flight. The second phase is the tracking phase controlling the receiving aircraft from the starting point to the 1000 (ft) behind the tanker at the desired lower point which is straight and lower from the tanker with 30 (ft) at this phase it is clear that the receiving aircraft speed profile maintained at almost constant speed as long as the receiving aircraft is away from the tanker then decelerating with different acceleration rates till starting the next phase, actually the smart fuzzy logic speed controller provide such profile according to the rule bases that was previously discussed. The third phase will switch the control to alignment controller which aligns the receiving aircraft with the center line of the tanker with steady level flight decelerating the speed to reach the tanker speed at the point of contact. Mean while the fuel boom will be extended down manually by using joystick until connecting the receiving valve in the upper surface of the receiving aircraft starting the refueling process. As shown in the previous figures the control strategy satisfies all the requirements stated for aerial refueling process such as flying qualities and the minimum estimated time (356 seconds) for initial relative distances of (38000 ft) with application of a DRYDEN gust model as a vertical gust . The previous figures show the effectiveness of using such integration to cope with the applied disturbance more than using LQR alone.

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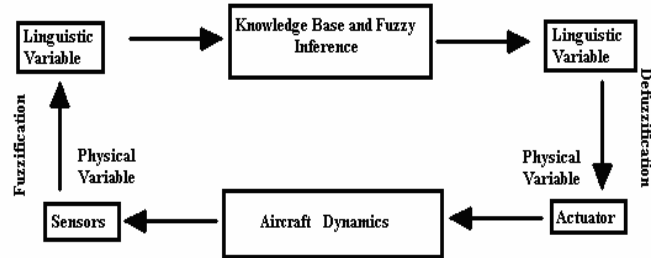

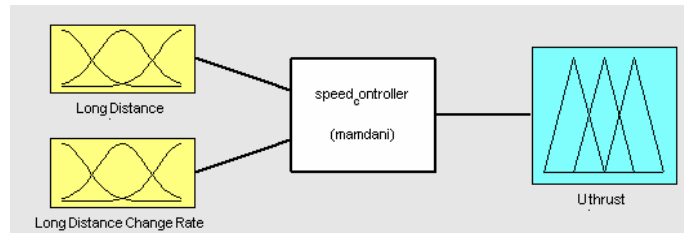Fig. 1. The structure of a Fuzzy Logic Control System

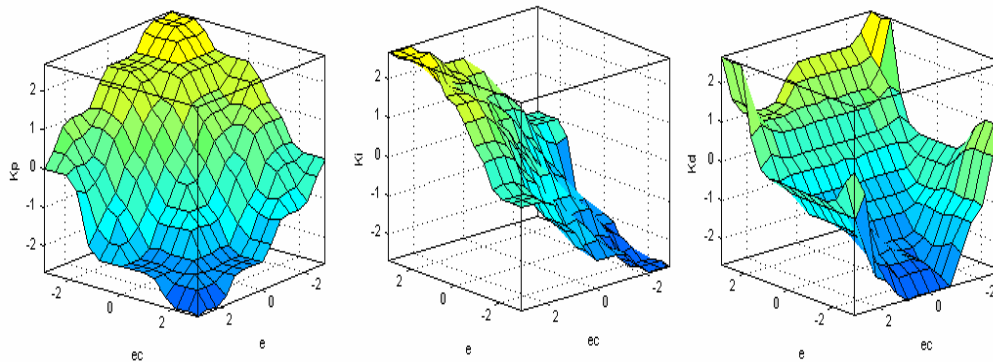

Fig. 2. Mamdani type fuzzy logic speed controller

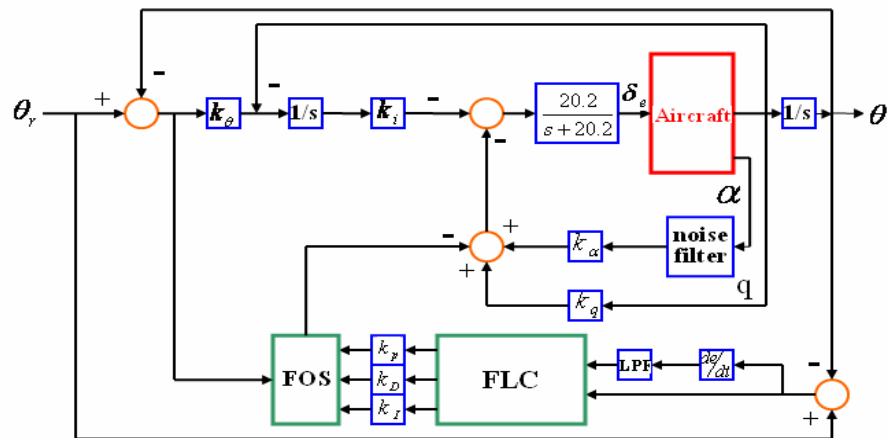Fig. 3. PID fuzzy logic controller output gains

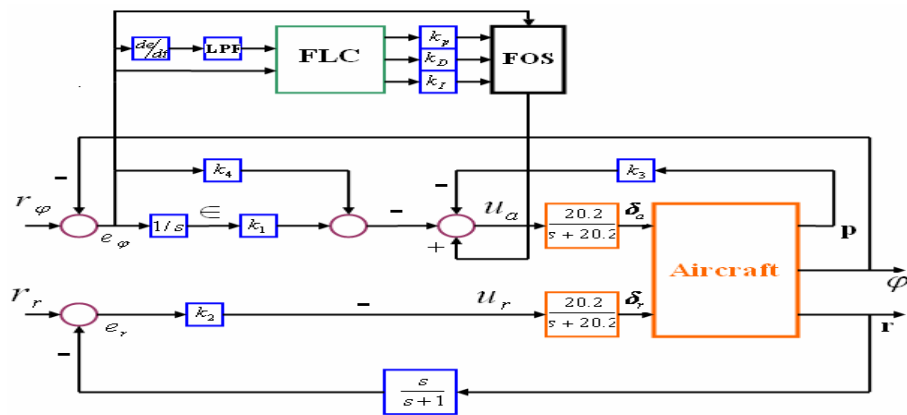Fig. 4. LQR integrated fuzzy control (LQRIFC) for pitch controller

Fig. 5. LQR integrated fuzzy control (LQRIFC) for lateral-directional controller
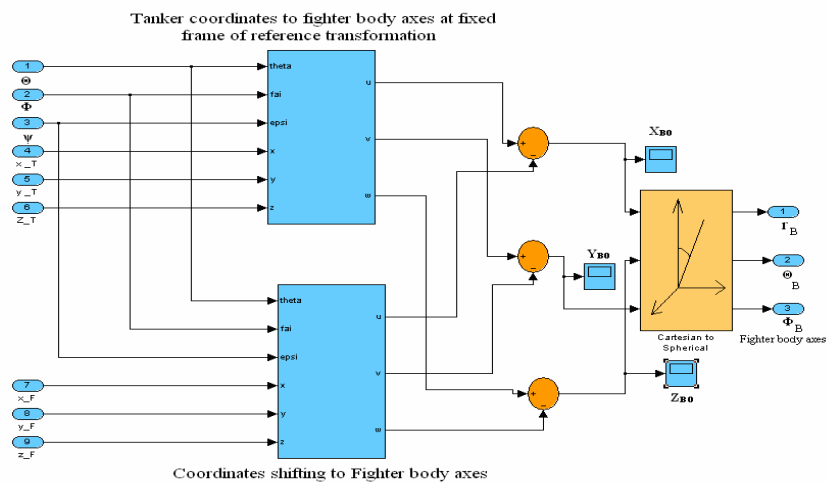
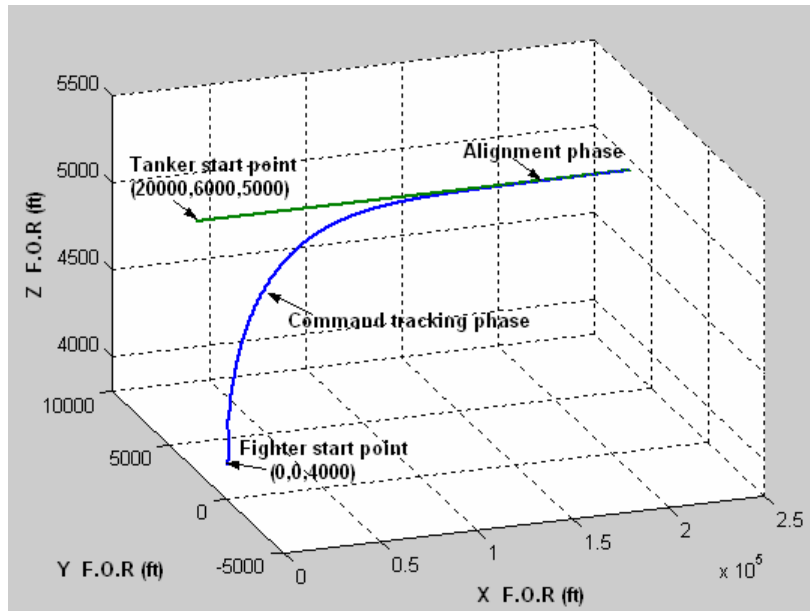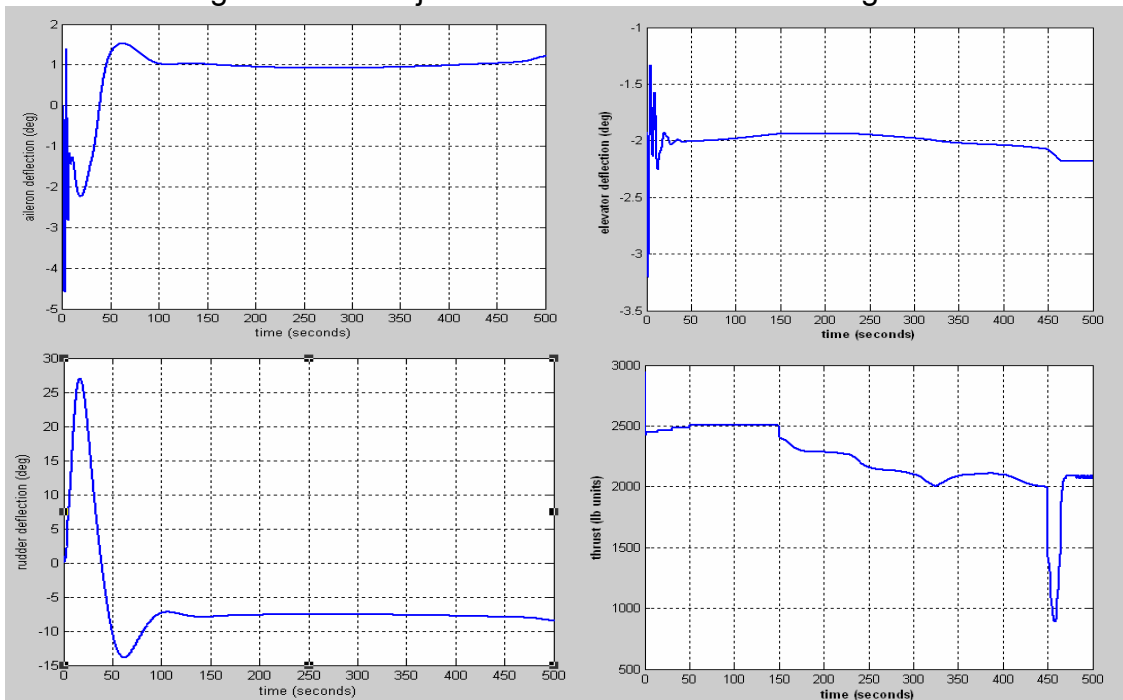Fig. 6. Tanker position transformation to aircraft wing axes
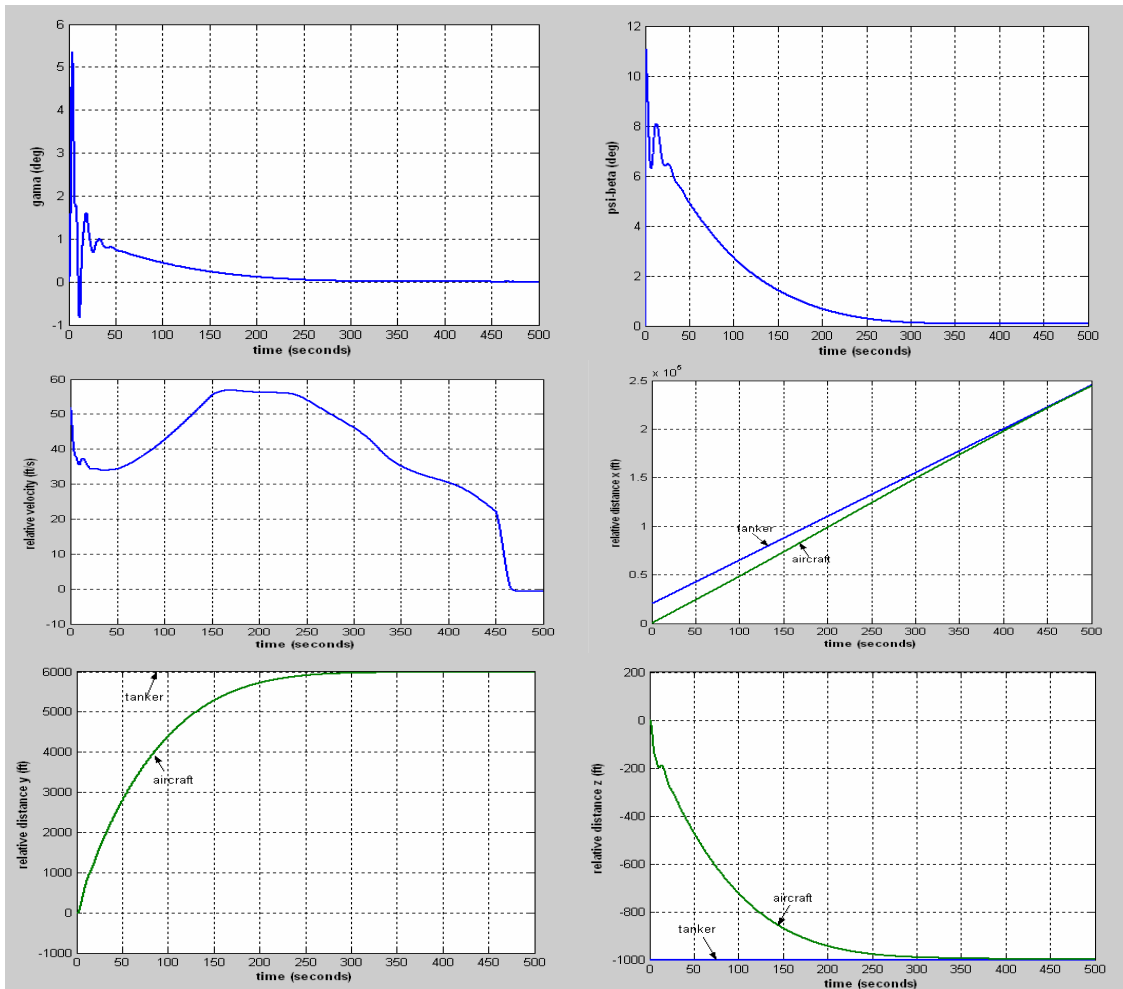
Fig. 7. Actual trajectories for tanker and receiving aircraft

Fig. 8. F-16 nonlinear model performance