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H Infinity Controller for Unmanned Aerial Vehicle Against Atmospheric Turbulence

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Abstract: Unmanned aerial vehicle experience different atmospheric uncertainties during their flight. These uncertainties caused the problem in the stability and the desired performance of the system. This research paper structured to nullify the influence of atmospheric turbulence and ground effect on the UAV. The models of Dryden turbulence is used as it is one of the major disturbances affecting the UAV and then H8 controller is computed using genetic algorithm to remove these uncertainties in the plant. This research managed to design controller so that it can meet both robustness and stability requirement. The designed methodology used several state points to validate the robustness of H8 controller. To investigate the performance of H8 and optimal controller LQR, the UAV plant model is simulated in Mat lab with the unknown atmospheric turbulence. The simulation results shows that robust H infinity control have achieved good transient and steady state performance than LQR optimal control against atmospheric turbulences.

Key words: UAV · Dryden turbulence · Genetic Algorithm Flight Control · LQR · H∞ · Matlab

INTRODUCTION

Control and stability of unmanned aerial vehicle is of great importance to accomplish the mission. The control of UAV requires too much attention because a good control is required to control uncertain system in uncertain environment. These uncertainties may be called matched uncertainties or mismatched uncertainties. Matched uncertainties are such kind of uncertainties that comes from Input channel and mismatched uncertainties are due to other channel. There are too much cross coupling between dynamics of UAV. So there should be robust and sensitive control scheme because due to variation in single dynamics may affect the whole model. Unmanned aerial vehicle dynamics also vary due to disturbance and external noise.

Designing a controller for UAV is a challenging task. UAV has diverse applications both for civil military use like in industrial plants, determination of ground operations and surveillance systems. It reduces lives of human being in risk to the inspection of remote operations and also cost as well to manage this operation. They are used in military for the support of troops as well as for civilian purposes such as for the inspection of crops in the agriculture [1].

There are many traditional schemes present that are used to control the UAV such as linear quadratic regulator [2, 3]. In [4], a PID control is employed to control the flight of UAV and stability but it is not remained good choice because Plant model is uncertain and environment as well. LQR is also not too favorable scheme because in UAV, dynamics may vary due to uncertainty i.e. matched or unmatched and due to external disturbances. Other strategies also present in research database like fuzzy logic base control design scheme [5]. H8 control remained a perfect choice by Zames [6, 7] has been employed to control both elevation and azimuth plane of UAV [8, 9].

Robust control is a good choice for unmanned aerial vehicle because it is attractive control to minimize external or internal disturbances and to achieve better stability. As system always contains uncertainties in it so in order to improve the robustness of controller and to meet the required performance specification H2 and H8 controller are mostly used. Atmospheric turbulence is always an issue of unmanned aerial vehicle that is why it is mostly the part of aviation research. While designing UAV various atmospheric turbulence parameters are taken into account like the speed and direction of wind etc. Design of traditional flight control system does not consider the atmospheric turbulence effect.

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Firstly we study the atmospheric turbulence model before studying its effect on unmanned aerial vehicle. Much research has been done on the atmospheric model they used various methods to study atmospheric turbulence and as the result scholars has defined the universal model of wind.

In order to apply robust control theory we must consider uncertainties in the mathematical model and the disturbance acting externally. We used H2 and H8 control method to design the H2 and H8 controller for the unmanned aerial vehicle. To cater with the external disturbances acting on the system we used H8 controller because it not only minimize the effect of these disturbance on the performance of the system but also provide good robust performance of the system.

Aircraft track and flight is affected by the atmospheric turbulence. High wind speed can cause the UAV to deviate it from its original route during the flight and can also cause problem during the take-off and landing.

During flight the turbulence is continuously effecting the UAV so it’s very important how the UAV response to these turbulence. To check the response of UAV for atmospheric turbulence, Dryden atmospheric turbulence model is used in this control problem. The details of Dryden atmospheric turbulence model is given in . The main contribution of this paper includes in following points.

- Optimal LQR controller is designed to stabilize the unmanned aerial vehicle without considering atmospheric turbulence
- H infinity controlled is designed to meet both performance as well as stability criteria when external Dryden turbulence is acting on the plant model that is major constraint in today flight controller design
- The simulation results with detail description shows that proposed controller has achieved both performance as well as stability criteria

Control Scheme: UAV is an unmanned aerial vehicle that has no pilot on board. It can be remotely controlled from ground stations or it can fly in auto mode by pre-planned mission that is feed into its control circuitry. The control of UAV is a great concern because it is highly uncertain and can cause damage, out of control due to atmospheric turbulence. The standard control scheme shown in Figure 1. In Figure 1, y is the system output contains observable and non-observable states. z1 and z2 are those output that we are interested to control it. Guidance controller is the major part in UAV control system. The whole flight control stability and accuracy depends on how well is the guidance controller.

This research deals with the atmospheric turbulence that is major concern in flight control of UAV. In order to plan perfect control scheme, first adopted optimal control theory using LQR and did analysis with the support of simulation results and checked the level of controller effort and accuracy to achieve robustness against the atmospheric turbulence. The standard H8 control system is shown in the Figure 2.

Where G(s) is the plant which is also our object which need to be controlled while K(s) is our controller while W is the external noise and the z is the output. While the input to the controller is y which is the measured output of plant and u is the output of the controller given to the plant input.

H8 controller is used to achieve the robust performance of the system. In this method firstly the control problem is expressed mathematically and then the controller is calculated to solve that control problem. The advantage of this controller is that it is applicable on the problems uncertainties and disturbances in it.

UAV State Space Modelling: Unmanned Aerial vehicle is highly uncertain, multivariable, time variant, coupled and unstable system.so before to design a perfect guidance controller, perfect modelling about dynamics necessarily required. A UAV is basically a 6DOF machine which has 3 linear and 3 rotational motions. To express the UAV in mathematical, law of physics can be applied to calculate. The schematic of unmanned aerial shown in Figure 3 that demonstrates the relationship between momentums, forces with the thrust provided by engine.

The state space realization of the above generalize system is:

$$\begin{aligned} \dot{x} &= Ax+B_1w+B_2u \\ z &= C_1x+D_{11}w+D_{12}u \\ y &= C_2x+D_{21}w+D_{22}u \end{aligned} \quad (1)$$

In our model of UAV the state variables are;

$x = [\beta \; p \; r \; \varphi \; \varphi_e]^T$

where β is the yaw angle and p is the pitch angle and r is the roll angle, $\varphi_e$is the evaluation index.

$u = [\delta_a, \delta_r]$

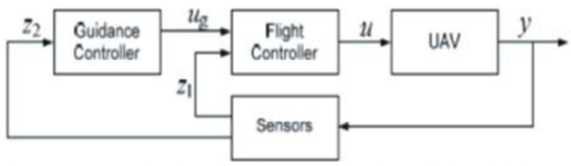

Fig. 1: Control scheme of Unmanned Aerial Vehicle

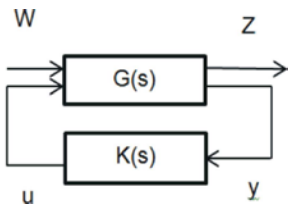

Fig. 2: Feedback Control Scheme

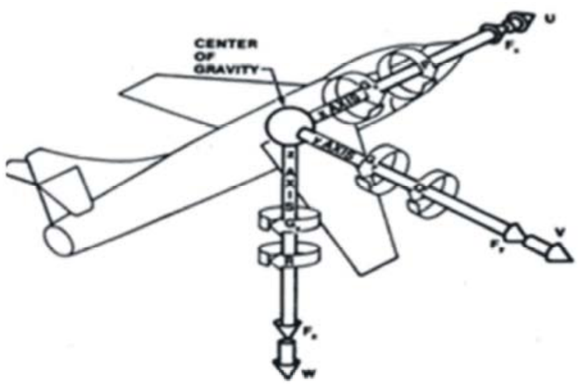

Fig. 3: Unmanned Aerial Vehicle

are the input to the plant from the controller or in other words it is a control input.

$w = [v_w w_{wy}\ v_{wx}\ \varphi_g]$

where $v_w w_{wy}\ v_{wx}$ are the turbulence of atmosphere while φ_g is the roll angle command.

$$[G(s)]=\begin{bmatrix} G_{11} & G_{12} \\ G_{21} & G_{22} \end{bmatrix}=\begin{bmatrix} A & B_1 & B_2 \\ C_1 & D_{11} & D_{12} \\ C_2 & D_{21} & D_{22} \end{bmatrix}$$

The uncertainties are also present in the system and they are affecting the performance and in some case can also affect the stability of the system so a system can only be robust if it can attenuate and cater with all the uncertainties affecting its performance. The uncertainties acting on the system can be additive and/or multiplicative. The values of uncertainties are calculated at the height of 1500m and the flight speed of 45m/s, following state space model parameters are calculated accurately to build accurate control law design U. The uncertainties acting on the system can be additive and/or multiplicative.

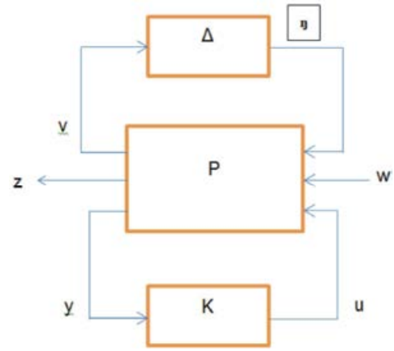

Fig. 4: General LFT Framework

The state space matrix of Unmanned Aerial Vehicle system G(s) shown in Figure 2 is given below:

$$A=\begin{bmatrix} -0.0709 & 02149 & -0.9889 & 0-2847 & 0 \\ -2.4179 & -6.7705 & 0.0188 & 0 & 0 \\ 0.4200 & -0.8852 & -0.0071 & 0 & 0 \\ 0 & 1 & 0.1505 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \end{bmatrix}$$

$$B_1=\begin{bmatrix} 0.0021 & 0 & 0 & 0 \\ 0.0711 & 6.7705 & -0.0188 & 0 \\ -0.0124 & 0.8852 & 0.0071 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & -1 \end{bmatrix}$$

$$B_2=\begin{bmatrix} 0.0003 & 0.0062 \\ -5.5394 & 0 \\ -0.5785 & 0.5226 \\ 0 & 0 \\ 0 & 0 \end{bmatrix}$$

$$C_1=\begin{bmatrix} 5 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0.5 & 0.5 \end{bmatrix}$$

$$C_2=\begin{bmatrix} 5 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0.5 & 0.5 \end{bmatrix}$$

$$D_{11}=\begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}$$

$$D_{12}=\begin{bmatrix} 0.5 & 0.5 \\ 0.5 & 0 \end{bmatrix}$$

$$D_{21} = \begin{bmatrix} 1 & 1 & 5 & 0 \\ 0 & 0 & 1 & 1 \end{bmatrix}$$

$$D_{22} = \begin{bmatrix} 0 & 0 \\ 0 & 0 \end{bmatrix}$$

Controller Design Section: In this section, a guidance controller will be designed for perfect trajectory plan of UAV. In this research, First Optimal control is designed using Linear Quadratic regulator and the results of LQR control shows that it is perfect strategy in terms of time domain specifications (Percentage overshoot, settling time, transient and stability) and tracking plan mission at some extent.

Optimal Controller LQR Design: In this section, First LQR control is implemented to control the UAV. LQR is most widely used control technique for perfect optimal control of Plant. The schematic of LQR design problem shown in Figure 5.

It deals with operating dynamics to make cost function minimum. When the system dynamics are described by differential equation, then cost is calculated by quadratic function called LQ. The solution of LQR problem is the control law U=-kx(t) where $K=R^{-1}B^TP$ where P is calculated by solving Ricatti equation $PA+A^TP+Q-PBR^{-1}B^TP=0$.

In LQR, Control law "u" is defined by reducing the Cost function defined below:

$$\int_0^{\infty}(x*Qx+u*Ru)dt \tag{2}$$

By using these matrices A, B1, B2, C1, C2, D11, D12, D21 and D22, G matrix is calculated by packing the A, B, C and D matrix. K matrix which is the controller gain matrix calculated by using lqr command in Matlab lqr(A, B, Q, R). In this command A, B are the matrices related to Plan. Matric Q and R are selected by hit/trial method but remember that Q is the semi positive matric and R is symmetric positive definite.

$$K = \begin{bmatrix} 0.6591 & -0.0685 & -1.9299 & -2.0663 & -0.9992 \\ -0.6384 & 0.0109 & 2.3073 & 1.9062 & 1.0404 \end{bmatrix}$$

H∞ Control design Based on Atmospheric Turbulence: In this section, H8 control law is defined and derived for the following UAV shown below.

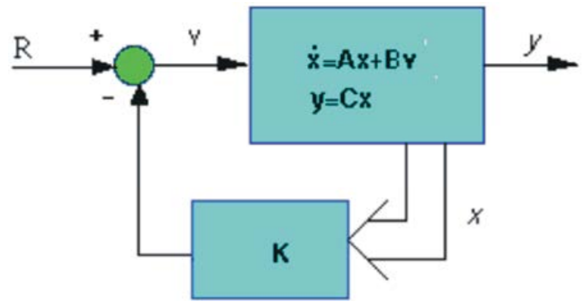

Fig. 5: State feedback Control using Optimal LQR

$$H = \begin{bmatrix} H_{11}(s) & H_{12}(s) \\ H_{21}(s) & H_{22}(s) \end{bmatrix} = \begin{bmatrix} A_1 & B_1 & B_2 \\ C_1 & D_{11} & D_{12} \\ C_2 & D_{21} & D_{22} \end{bmatrix}$$

where $H_{11}(s)$◎ R^{p*q}, $H_{12}(s)$ ◎ R^{p*m}, $H_{21}(s)$ ◎ R^{r*q}, $H_{22}(s)$ ◎ $R^{r*m}$is the real coefficient rational matrices.

The problem is to find optimal controller K such that $\|T_{ZW}\|_{\infty}$is internally stable and minimized where the closed loop transfer function w to z is:

$$T_{zw} = H_{11}(s) + H_{12}(s)K(1-H_{22}(s)K(s))^{-1}H_{21}(s) \tag{3}$$

This research used both DGKF and reduced order H_{∞};a direct minimization method to solve H infinity control problem for this UAV.

In order to apply DGKF to above System H(s), there should be following conditions holds.

- (A, B_1), (A, B2)must be stable and also (C_1, A), (C_2, A) must be detectable.
- $D_1^T[C_1\ D_{12}]=[0\ 1]$.
- $\begin{bmatrix} B_1 \\ D_{21} \end{bmatrix} D_{21}^T = \begin{bmatrix} 0 \\ 1 \end{bmatrix}$

The two Hamiltonian matrix is given below.

$$H_{\infty} = \begin{bmatrix} A & \gamma 2B^1B^2T - B^1B^2 \\ -C^1C^2T & -AT \end{bmatrix} \tag{4}$$

and

$$J_{\infty} = \begin{bmatrix} AT & \gamma 2C_1C_2T - C_1C_2 \\ -B_1B_2T & -AT \end{bmatrix} \tag{5}$$

The following theorem should hold in order to satisfy$\|T_{ZW}\|_{\infty}<\gamma$

Theorem 2-1:[7, 8]

$\|T_{ZW}\|_\infty < \gamma$ exists if and only if following conditions holds:

- H_∞ ε dom(Ric) and $X := Ric(H_\infty) \geq 0$
- J_∞ ε dom(Ric) and $Y := Ric(J_\infty) \geq 0$
- $p(XY) > \gamma^2$

if these conditions holds for system matrix H then the controller K is.

$$K = \begin{bmatrix} A^\wedge & -ZL \\ F & 0 \end{bmatrix}$$

where $A^{\wedge} = A + \gamma B_1 B_1^T X + B_2 F + ZLC_2$

$F = -B_2^T X$, $L = -YC_2^T$, $Z = (1-\gamma^2 YX)^{-1}$

Let start from both upper bound and low bound value of γ such that condition (i), (ii) satisfied and also $p((X_u)(Y_u) < \gamma_u^2$, $p((X_l)(Y_l) > \gamma_l^2$.

For a search of optimal γ value, Let's start from $\gamma_u = 80$ and $\gamma_l = 1.4678$, when γ closes to optimum value such that condition (i) and condition (ii) holds then the matrix $(1-\gamma^2 YX)$ will be singular. At this time, the optimum controller K can be written as:

$$K_{opt} = \begin{bmatrix} Ac & Bc \\ Cc & Dc \end{bmatrix}$$

where,

$$A_c = ◎◎^{-1}[U_1^T A_D w_1 - U_1^T A_D w_2 (U_2^T A_D w_2) U_2^T A_D w_1]$$
$$B_c = ◎◎^{-1}[-U_1^T L + U_1 A_D V_2 (U_2^T A_D w_2) U_2^T L]$$
$$C_c = FV_1 - FV_2 (U_2^T A_D V_2)\, U_2^T A_D V_1$$
$$D_c = FV_2 (U_2^T A_D V_2) U_2^T L$$

The desired optimal controller gain at optimum gamma calculated $\gamma = 1.789$.

Minimization Method for Reduced Order H8 Controller
The aim is to design a Controller K.

$$K =; \begin{Bmatrix} \dot{x}c = AcXc + Bcy \\ \\ U = CcXc \end{Bmatrix} \quad (6)$$

where $U = K(s)y$
and $K = C(S^*I - A_c)^{-1} B_c + D_c$

From the state space model of UAV and controller, the closed loop system state space can be written as:

$$\dot{x}_{cl} = A_{cl} x_{cl} + B_{cl} w$$
$$z = C_{cl} x_{cl} + D_{cl} w,$$

where:

$$\dot{x}_{c1} = \begin{bmatrix} \dot{x} \\ \dot{x}c \end{bmatrix}, A_{c1} = \begin{bmatrix} A + B_2 DcC_2 & B_2 Cc \\ B_2 & Cc & Ac \end{bmatrix}, B_{c1} = \begin{bmatrix} B_1 + B_2 DcD_{21} \\ BcD_{12} \end{bmatrix}$$
$$C_{c1} = [C_1 + D_{12} DcC_2 + D_{12} Cc], D_{c1} = [D_{11} + D_{12} DcD_{21}]$$

Such that control loop system H_{cl} with state $X_{cl} = [X\ Xc]^T$ remains stable for all possible trajectories with necessity upper bound on H_2 or H_∞ performance.

The closed loop transfer function from w to z can also be written as:

$$T_{zw}(s) = C_{cl}(sI-A)^{-1} B_{cl} + D_{cl}$$

Now Lets designed the controller K such that $\|T_{ZW}\|_\infty < \gamma$ for some cost $\gamma > 0$. Where Norm that $\|T_{ZW}\|_\infty$ is the maximum singular value of transfer from w to Z shown in Figure 2. In above we have assumed atmospheric turbulence as disturbance in our model so the effort of H infinity bounds the gain of overall transfer function below value γ.

In this section, the plan is to find controller K using direct minimization method for reduced order H_∞ controller. The controller design K requires the minimization of $\|T_{ZW}\|_\infty$ such as:

$$\max(real(\lambda(A_k))) < \epsilon_1 \quad (7)$$
$$\max(real(\lambda(A_c))) < \epsilon_2$$

Here λ is Eigen value and ϵ_1 and ϵ_2 are some negative number close to zero to ensure stability.

Let's modify the controller dimension $X_c = TX_t$, now controller state space model can be re written as:

$$\dot{x}_t = T^{-1} A_c T x_t + T^{-1} B_c y$$
$$u = C_c T x_t + D_c y$$

where:

$$T = [B_{cl}\ A_c B_{cl}\ A_c^2 B_{cl} \ldots\ldots\ldots A_c^{k-1} B_{cl}]$$

The H_∞ controllers' matrix obtained using genetic algorithm by solving constraints of equations 7 as follows.

$$A_c = \begin{bmatrix} -0.0742 & 0.2116 & -3.9907 & -2.2162 & -2.5009 \\ -2.4233 & -6.7759 & -5.0581 & -2.5196 & -2.5196 \\ 0.4162 & -0.8890 & -3.6186 & -1.8129 & -1.8129 \\ -0.0011 & 0.9989 & -0.8468 & -0.4987 & -0.4987 \\ 9.9954 & -0.0046 & -4.2122 & -2.1061 & -3.1061 \end{bmatrix}$$

$$B_c = \begin{bmatrix} 0.0017 & 3.0018 \\ -0.1923 & 5.0769 \\ -0.1975 & 3.6115 \\ -0.0001 & 0.9973 \\ 0.0009 & 4.2122 \end{bmatrix}$$

$$C_c = \begin{bmatrix} 0 & 0 & 0 & -1 & -1 \\ -10 & 0 & 0 & 1 & 1 \end{bmatrix}$$

RESULTS AND DISCUSSIONS

In this section, will discuss the implementation of Optimal control LQR for UAV and will see the level of effort contributed by this controller to make perfect desired tracking mission plan using Matlab/Simulink. Then other part of this paper further extended the control scheme using robust H8 control with or without consideration of Atmospheric turbulence on Unmanned Aerial Vehicle . This research adopted both DFKF's state space mode and reduced fixed order minimization method to obtain H8 solution. A reduced fixed order H8 technique used to implement robust control on UAV but in case of DGKF's; only theoretical work is discussed for appropriate control law as a part of research in this paper.

Implementation Using LQR: Let's first see the Optimal control effort on UAV model. The response of system with step input using LQR controller with optimal gain are shown from Figure 6-10. In below responses, dotted lines show desired response while blue line shows actual response.

$$K = \begin{bmatrix} 0.6591 & -0.0685 & -1.9299 & -2.0663 & -0.9992 \\ -0.6384 & 0.0109 & 2.3073 & 1.9062 & 1.0404 \end{bmatrix}$$

It is clearly seen from Figure 6 that states convergence to zero is not achieved quickly and even before 200s, the system has considerable overshoot and large settling time even without extra atmospheric turbulence. The perfect control in UAV is a great concern and so no one desire above response in online flight control scheme. Thus LQR is not good choice for Unmanned Aerial vehicle so an approach to H8 control should be analyzed for desired response.

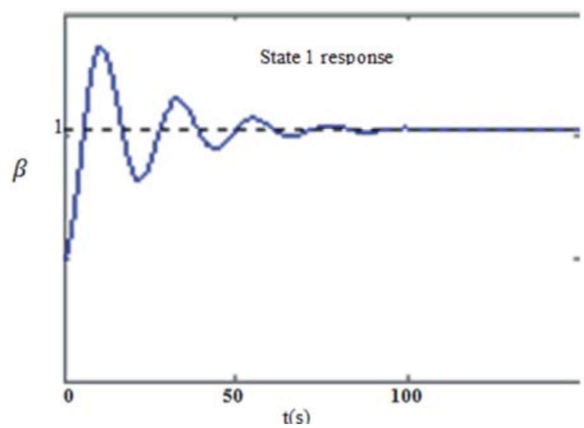

Fig. 6: State 1 response Pitch angle versus time

Implementation Using Robust H_∞ Control: In this section, the effort to design robust H_∞ controller will be done without and with atmospheric turbulence.

The H2 and H_∞ matrices have been calculated in section IV with matrices A_c, B_c and C_c for packed Plant as follows:

$$[G(s)] = \begin{bmatrix} G_{11} & G_{12} \\ G_{21} & G_{22} \end{bmatrix} = \begin{bmatrix} A & B_1 & B_2 \\ C_1 & D_{11} & D_{12} \\ C_2 & D_{21} & D_{22} \end{bmatrix}$$

The response of the system with H8 Controller shown in Figure 8 when atmospheric turbulence to system model is zero. It is clearly seen that a robust H infinity control has achieved appreciable peak time as well as well as settling time for a UAV model flight operation. Hence the simulation results are evidence of perfect control effort of H8 for UAV model.

Now next see the H8 control effort with the addition of atmospheric turbulence and examine the control effort of our proposed controller against the wind disturbance that tries the UAV to disturb it from its appropriate trajectory planning.

To see the atmospheric turbulence effect in our system, Dryden wind turbulence continuous block is taken that uses Dryden spectral representation to add external disturbance by use of appropriate filter. The more details of Dryden atmospheric turbulence function are present in the Mat lab help file as well as in.

In our example, control problem is simulated by taking following numerical values height 1500m; aircraft speed V is 45m/s to generate. It is the Dryden turbulence that is added in control loop and the effort of controller is tested against this turbulence.

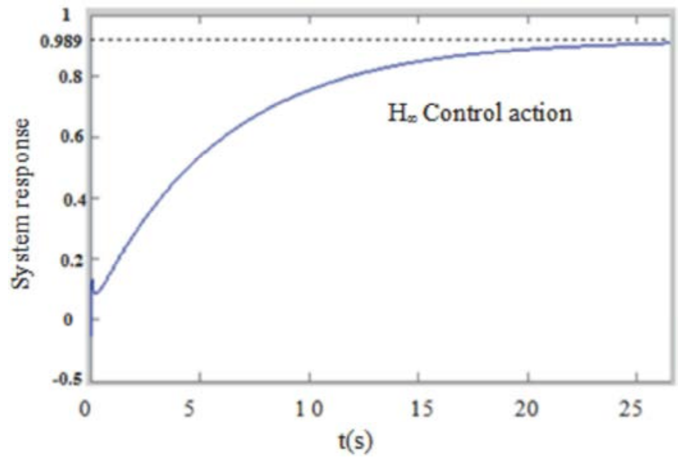

Fig. 8: H$_\infty$ Control action on system response (pitch)

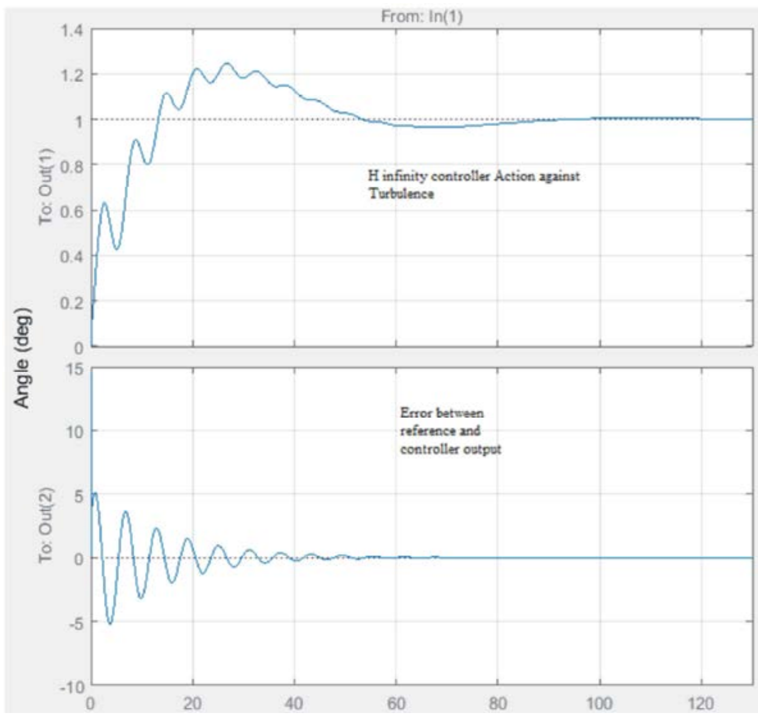

Fig. 9: System response with atmospheric turbulence using H$_\infty$ Controller (pitch)

The resulting response of H8 control with wind turbulence in the system model shown in figure 9. It is clear from simulation results of Figure 8 and 9 that H8 is more robust technique against the Dryden wind turbulence and it stabilizes the plant very fast. In comparison with LQR, it is clear that H8 controller effort has minimum overshoot and appreciable settling time and it also gives the desired result with perfect accuracy.

By deeply analysing the time domain specifications of robust H infinity controller effort against the atmospheric turbulence, it can be visualized from Figure 9 that at the start of 20s, there is considerable overshoot and then oscillation starts die out after 20s. Also there is almost less than 0.1 steady state error after 20s. Hence robust H infinity controller has achieved stability and perfect dynamic response with atmospheric turbulence than ordinary LQR controller effect. Hence by simulation results, it is concluded the robust H Infinity controller stabilizes the plant very quickly and attain the desired results with perfect accuracy against atmospheric turbulence.

CONCLUSION

The control of unmanned aerial Vehicle is a very difficult task against atmospheric turbulence. It is a very serious issue in today autonomous aerial vehicle. The first contribution of this paper is to analyse LQR control effort against the turbulence. The simulation results and above discussion shows that response generated by LQR is not appreciable by its few limitation that are mentioned in control design section .The second contribution of this is to design of robust H_∞ Controller for Unmanned Aerial Vehicle with consideration of atmospheric turbulence. In comparison with LQR, LQR is not suitable one controller to consider atmospheric turbulence in the UAV model to achieve desired objectives due to maximum overshoot as well as too much settling time. The simulation results of Robust H_∞ show that the designed controller has overcome all the uncertainties that affect the UAV during its flight. The designed controller also has achieved good dynamic performance as well as stability objectives so it is concluded that the proposed controller can maintain the stable flight of UAV even when there is high atmospheric turbulence.

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