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Unmanned Aerial Vehicle Pitch Optimization for Fast Response of Elevator Control System

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Abstract**—***The flight dynamics of an Unmanned Aerial Vehicle (UAV) is the science of its orientation and control in three dimensions. The three primary orientations include: the Pitch, the Roll and the Yaw. The rear part of the tailplane is known as the elevator control of an UAV pitch (the rotating around the transversal axis). Flight route deviations and flight altitude variations due to hash weather conditions such as shock waves or thunder storm and the wind speed/direction during flight greatly affect the pitch of UAV. Consequently, series of UAV mishaps (air crash) caused by pitch control faults have been recorded in the aviation industry in recent times. Such pitch control faults are mostly caused by inadequate speed and accuracy in the automatic control of UAV pitch mechanism or the tail elevator. The main goal of this research is to design a classical controller that optimizes the pitch control response speed and accuracy of an UAV with built-in autopilot. A PID controller has been design and fine-tuned with MATLAB PID Tuner to obtain suitable gains for faster and accurate response of the UAV elevator. The improved control parameters achieved in verifying the model and design by simulation with MATLAB/Simulink are the settling time of 0.436 seconds, the rise time of 0.113 seconds, the percentage overshoot of 9.43% and a steady-state error less than 2%.*

Keywords**—***PID Controller: Flight Dynamics: UAV Pitch Control: Flight Control System: UAV Tail Elevator Control System.*

I. INTRODUCTION

Most Unmanned Aerial Vehicle (UAV) designs in modern times depend heavily on automatic control system to monitor and control many of their subsystem [1]. A machine that is able to fly by gaining support from the surrounding air or the planet is known as an aircraft. Aircraft can be categorised according to the lift type, propulsion, usage etc. the science of aircraft orientation and control in three dimensions is called Flight Dynamics. There are three major parameters considered in flight dynamics or the accurately controlled movement of an aircraft. These are the pitch, roll, and yaw angles of rotation around the three axes about the aircraft’s centre of mass. The rotation of an UAV about the longitudinal axis is called the roll. The roll causes an up-down movement of the wing tips measured by the roll or bank angle. Similarly, the rotation of an UAV about the vertical axis is known as the yaw. The yaw brings about a side-to-side movement of the UAV nose known as sideslip. The pitch of an UAV is its rotation about the sideways horizontal axis which causes an up-down movement of the nose measured by the angle of attack.

Modern aircraft are designed to operate at a wide range of flight conditions, which are characterized by wide variations in angle of attack, sideslip angle and body axis rotational rates [2]. The control and stability of an aircraft's rotation about the pitch, the roll and the yaw axes, is the main principle of Flight dynamics. The most essential among the three major parameters of flight dynamics is the pitch which is controlled by the rear part of the tailplane known as the elevator. Changes of pitch are caused by the deflection of the elevator, which rises or lowers the nose and tail of the aircraft [1]. The control of an aircraft's take-off timing, flight attitude, flight range and landing angle require an accurate control of the pitch. The pitch angle of an aircraft is controlled by changing the angle and equally the lift force of the rear elevator.

Normally, a flight is controlled by a system called the Flight Control System (FCS). In the early days of aircraft technology, the FCS was mechanically carried out by means of cables and pulleys known as fly-by-wire [3]. However, due to recent advances in aircraft control, most flights are now automatically controlled by computers. Modern aircraft such as UAVs now have a variety of automatic control system that helps in flight navigation, flight management and augmenting the stability characteristic of the airplane [4]. The automatic pitch control of an aircraft is a longitudinal problem which requires an autopilot. An autopilot is a pilot relief system that assists in sustaining an attitude, heading, flying to navigation or landing references [5].

An Unmanned Aerial Vehicle (UAV) is simply an aircraft without a human pilot aboard. It is commonly known as a drone. The pilot in the cockpit is replaced by an automatic avionics control system that communicates with the ground control stations. Examples of UAs are: Camera-Toting Quadcopters, MQ6-Predator, Pollution-fighting Pinecone, Border-Monitoring drones etc. They are used for disaster management, toxic chemical detection, computational resources, surveillance, drone strikes and border security [8]. Also, UAVs are deployed to areas like law enforcement, time progression (astronomical observations), fire fighting, communication relays, search and rescue [8].

Most UAVs employ Proportional Integral Derivative (PID) controllers or classical controller for adequate control. This means that a well-tuned PID controller, to some acceptible extent, can be applied to controlling an UAV. In practice, a UAV uses a combination of PID feedback controllers to generate the control efforts of conventional control surfaces and engine throttle [13].

Flight route deviations and flight altitude variations due to hash weather conditions such as shock waves or thunder storm and the wind speed/direction during flight greatly affect the pitch of UAVs. Also, poor response of the tail elevator to pitch control signal adversely affects the UAV performance. Consequently, series of UAV mishaps (air crash) caused by autopilots pitch control faults have been recorded in the

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aviation industry in recent times. One of the major problems of flight control system is due to the combination of nonlinear dynamics, modelling uncertainties and parameter variation in characterizing an aircraft and its operating environment [6].

II. LITERATURE REVIEW

Several of previous research work has been done in the field of aircraft pitch control system. The design aspects of a robust PID controller for higher-order systems was carried out by Kada and Ghazzawi [7], Lwin et al. [8]**,** in a recent research work, proved that Kalman and PID controller can be used to design Air Vehicles (AV) formation flight control system for speed and pitch angle. The use of Unmanned Aerial Vehicle in sensitive and important operation requiring autopilots that can be tuned for Micro Aerial Vehicle (MAV) in different environment conditions was investigated by Haq [9]. The Sum of Squares (SOS) programming approaches were used by Krishnaswamye et al. [10] to analyze the stability and robustness properties of the controlled pitch axis of a nonlinear model of an Aircraft etc.

The main purpose of this research is to design a classical controller that optimizes the pitch control response speed and accuracy of an UAV with built-in autopilot for a better performance. This in turn improves the response of the UAV's elevator system which invariably determines the efficiency of its pitch angles.

III. UAV PITCH CONTROL MODEL

The equations governing the motion of an Unmanned Aerial Vehicle (UAV) can be classified into the longitudinal and lateral equations. The longitudinal equations an aircraft are the equations in a longitudinal, or pitching, plane under steady-flight conditions while the lateral equations are the equations of motion about the lateral plane steady-flight conditions. A description of the modelling of pitch control longitudinal equation of an UAV is provided in this section. The system of longitudinal dynamics is analysed and the transfer function and state equation are derived.

The flight dynamics of an UAV can be represented mathematically by the equations of forces and moments acting on it as shown in figure 1.0. The aerodynamics moment components for Roll, Pitch and Yaw axis are represented as L, M and N. There are four aerodynamic forces acting on an aircraft which includes; thrust, drag, lift and weight. The thrust is the forward force produced by the power propeller. The drag caused by air resistance and other aerodynamic factors tends to oppose the forward motion of an aircraft. Weight is the load of the aircraft itself. Lift opposes the downward force of weight. These aerodynamic forces and the gravitational force acting through CG (Centre of Gravity) determine the moments of an aircraft.

The pitch control system is considered in Fig 1.0 with the following parameters:

X_b = angle of attack

Y_b = side force

Z_b = vertical force, represent the aerodynamics force components.

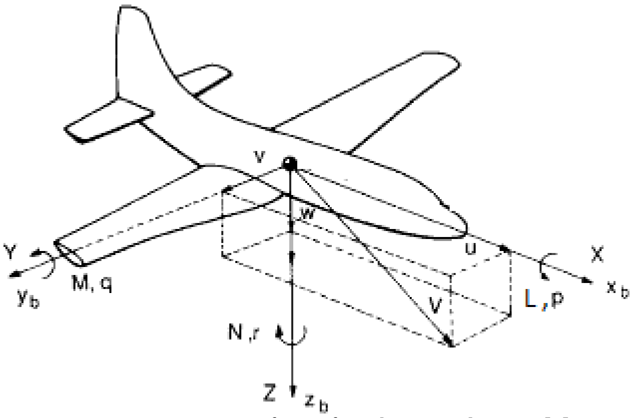

Fig. 1.0. A Description of aircraft pitches control system [6].

The forces, moments and velocity components in the body fixed coordinate of aircraft system are shown in fig 2.0 and 3.0.

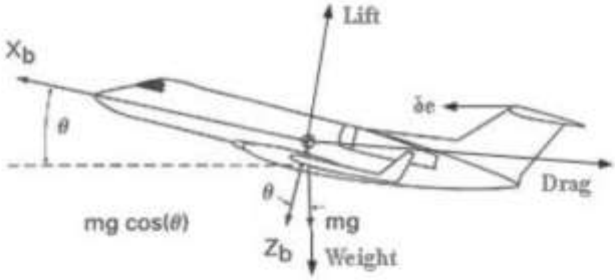

Fig. 2.0. The force, moments and velocity of an UAV [6].

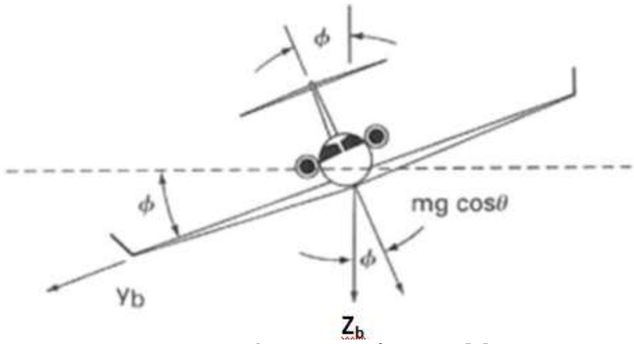

Fig. 3.0. Pitch Dynamics of an UAV [6].

The orientation of aircraft (pitch angle) in the earth-axis system and elevator deflection angle are represented as:

θ = pitch angle φ = roll angle, ϕ = yaw angle, and δe = angle of sideslip.

The mathmatical model for pitch control of an UAV can be derived from figs 1.0, 2.0 and 3.0. The dynamic equations of motion of force and moment are determined as follows.

$$X - mgS_{\theta} = m\left(\dot{u} + qv - rv\right) \qquad 1.0$$

$$Z - mgC_{\theta}C_{\phi} = m\left(\dot{w} + pv - qv\right) \qquad 2.0$$

$$M = l_y q + rq\left(l_x - l_z\right) + l_{xz}\left(p^2 - r^2\right) \qquad 3.0$$

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The term M = pitching moment, X and Z are the components of the aerodynamic propulsive forces acting on the aircraft, m = aircraft mass, g = gravitational acceleration, S_θ = pitch reference area, and l_x, l_y and l_z are the moments of inertia, C_θ and C_φ are aerodynamic force coefficients, u = longitudinal velocity, v = lateral velocity, w = normal velocity, p = row rate, q = pitch rate, and r = yaw rate. α and β are represents as the angle of attack and sideslip.

Equations 1.0, 2.0, and 3.0, can be linearized assuming a symmetric flight condition and constant propulsive forces $p_0 = q_0 = r_0 = v_0 = \varphi_0 = w_0 = \phi_0 = 0$ to be obtained the following equations [13]:

$$\left(\frac{d}{dt} - X_u\right)\Delta u - X_w \Delta w + \left(g\cos\theta_0\right)\Delta\theta = X\delta_e \qquad 4.0$$

$$-Z_u\Delta u + \left[(1-Z_w)\frac{d}{dt} - Z_w\right]\Delta w - \left[(u_0 + Z_q)\frac{d}{dt} - g\sin\theta_0\right]\Delta\theta$$
$$= Z_{\delta_e}\Delta\delta_e \qquad 5.0$$

$$-M_u\Delta u - \left(M_w\frac{d}{dt} - M_w\right)\Delta w + \left(\frac{d^2}{dt^2} - M_q\frac{d}{dt}\right)\Delta\theta$$
$$= Z_{\delta_e}\Delta\delta_e \qquad 6.0$$

where $\Delta\delta_e$ = change in elevator angle and $\Delta\theta$ =change in pitch angle. If the change in pitch rate is represented by Δq, it implies that the change in pitch rate is the first derivative of the pitch angle as in equation 7.0.

$$\Delta q = \Delta\frac{d}{dt}\theta \qquad 7.0$$

Taking the Laplace Transform of both sides of equation 7.0,

$$\Delta q(s) = s\Delta\theta(s) \qquad 8.0$$

The transfer function of the aircraft pitch dynamics can be obtained as the Laplace Transform ratio of the change in pitch angle, to the change in elevator angle, as in equation 9.0.

$$\frac{\Delta\theta(s)}{\Delta\delta_e(s)} = \frac{1}{s}\frac{\Delta q(s)}{\Delta\theta(s)} \qquad 9.0$$

The transfer function of the pitch control system can be obtained as the Laplace Transform of the change in pitch angle to the change in elevator angle based on equation 9.0 as shown in equation 10.0.

$$\frac{\Delta\theta(s)}{\Delta\delta_e(s)} = \frac{1}{s}\frac{-\left(M_{\delta_e} + \frac{M_\alpha Z_{\delta_e}}{u_0}\right)s - \left(\frac{M_\alpha Z_{\delta_e}}{u_0} - \frac{M_{\delta_e} Z_\alpha}{u_0}\right)}{s^2 - \left(M_q + M_\alpha + \frac{Z_\alpha}{u_0}\right)s + \left(\frac{Z_\alpha M_q}{u_0} - M_\alpha\right)} \qquad 10.0$$

By substituting the longitudinal stability derivatives parameters values from previous research by Wahid et al [6] into equation 10.0 and simplifying the transfer function G(s) is obtained as equation 11.0.

$$G(s) = \frac{\Delta\theta(s)}{\Delta\delta_e(s)} = \frac{12.01s + 22.302}{s^3 + 0.9523s^2 + 12.88s} \qquad 11.0$$

IV. PERFORMANCE SPECIFICATION

a) Percentage overshoots less than 10% to a unit step input.
b) Settling time less than 0.5 seconds to a unit step input.
c) Rise time of less than 0.2 seconds to a unit step input
d) Steady-state error less than 0.2%

V. AIRCRAFT PITCH CONTROLLER

A Proportional Integral Derivative (PID) controller is a generic control loop feedback mechanism widely used in industrial control systems and regarded as the standard control structures. A PID controller, sometimes called three-term control, computes error values as the differences between measured process variables and a desired setpoint. The controller is primarily designed to minimize the error by adjusting the process using a set of manipulated variable. The three major components of a typical PID controller are: proportional controller, integral controller and derivative controller. The overall mathematical description of linear relationship existing between the controller output, u(t) and the error, e(t) is expressed as equation 1.9.

$$u(t) = K_p e(t) + K_i\int e(t)dt + K_d\frac{de(t)}{dt} \qquad 12.0$$

In order to stabilize this system and eventually meet the given performance specification in section IV, a well tuned feedback PID controller is added to the system to achieve a closed-loop.

The overall block diagram of an aircraft closed-loop pitch control system is shown in fig 4.0.

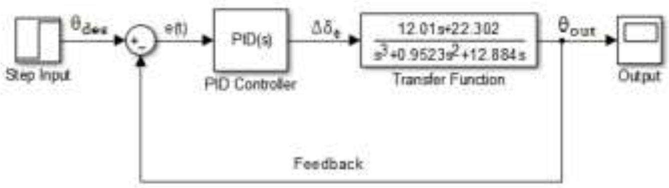

Fig. 4.0. Schematic Diagram of an UAV Pitch Control System.

The desired pitch angle of the UAV resulting from the elevator is θ_{out}, the input pitch command to the aircraft is θ_{des}, and is the output pitch which serves as a negative feedback. The transfer function in Equation 11.0 was simulated with the PID Controller in equation 12.0. The controller was tuned to obtain the most suitable parameter values using MATLAB/Simulink PID tuner. The PID controller gains obtained are K_p=10.7142, K_i=2.4801 and K_d=0.92844. Therefore the actual PID controller is

$$G_{PID}(t) = 10.7142(t) + 2.4801\int e(t)dt + 0.92844\frac{de(t)}{dt} \qquad 13.0$$

Taking the Laplace Transform of equation 13.0,

$$G_{PID}(s) = 10.7142 + 2.4801\frac{1}{s} + 0.92844s \qquad 14.0$$

VI. RESULTS AND DISCUSSION

In this section the analysis and discussion of the verified results obtained from the simulation of the UAV pitch control system model and the designed controller are presented. The

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results include the step responses of the aircraft mathematical model transfer function. The initial step responses of the UAV pitch control system without a well tuned Proportion-Integral-Derivative (PID) Controller is investigated by using MATLAB/Simulink simulation as shown in fig 5.0.

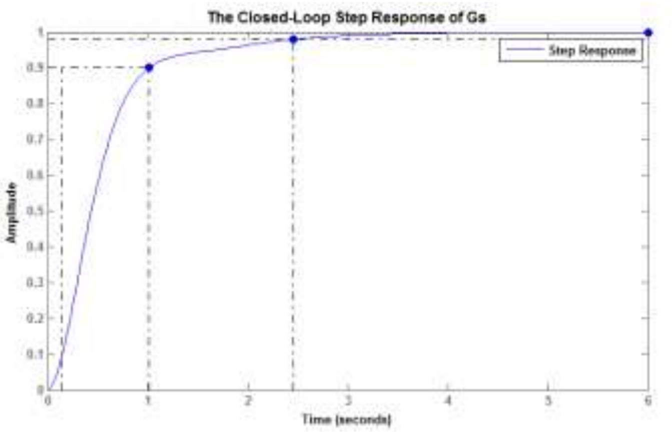

Fig. 5.0. Initial Step Response of the Pitch Control Transfer Function.

From plot, the unit step response of the UAV pitch control system with the settling time of 2.436 seconds, rise time of 1.01 seconds and percentage overshoot of 0.43%, does not satisfy the performance specification earlier state in section IV. It can be inferred from the plot that the open-loop response the system is not acceptably optimized.

The step response of the aircraft pitch control when a well tuned PID Controller was simulated using MATLAB/Simulink. The PID Controller was tuned with a Matlab/Simulink PID tuner application. The results of the simulation for the system with transfer function are shown in figure 6.0. From the unit step response plot for the UAV pitch control system with well-tuned PID Controller, $G_{PID}(s)$ shown in figure 6.0, the control parameters obtained are: the settling time of 0.436 seconds, the rise time of 0.113 seconds, the percentage overshoot of 9.43% and a steady-state error less than 2%.

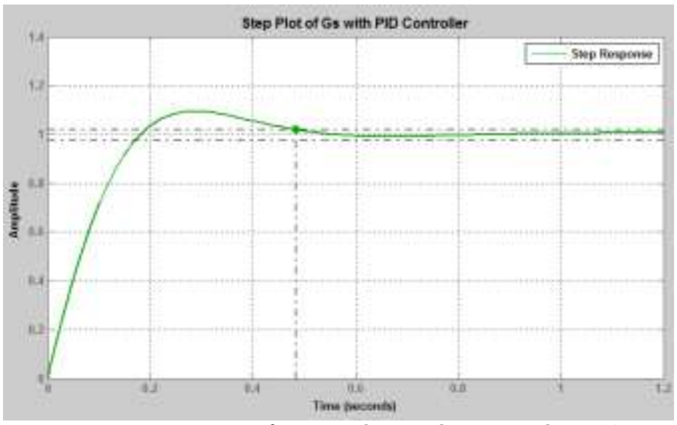

Fig. 6.0. Step Response of UAV Pitch Control System with $G_{PID}(s)$.

The settling time shows an optimized response of the aircraft elevator and equally the pitch to control signals. Also, the steady-state error, the percentage overshoot and the rise time indicate improvements in the fastness and accuracy of the UAV's elevator.

VII. CONCLOSION

This research presented the design of a classical controller that optimizes the performance of the pitch control system of an Unmanned Aerial Vehicle (UAV). Pitch control system is one that requires a pitch controller to maintain the pitch angle at a desired value. A PID controller was successfully designed and integrated to pitch control system. The PID controller has been fine-tuned with MATLAB/Simulink and MATLAB PID tuner to obtain suitable gains for faster and accurate response of the UAV elevator. In the simulation figures, it was possible to prove that the integrated PID controller and pitch control system provided the desired dynamics with great fastness and accuracy. The simulation results show that, the designed pitch controller relatively gave a better performance for UAV system. Based on the analysis it was demonstrated that the settling time, percentage overshoot, steady state error and rise time were greatly improved.

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