ISSN 2229-5518

Integrated Modelling and Control of Airspeed of Aircraft

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Abstract—Aircrafts are highly nonlinear in nature. The flight control system is nonlinear with respect to signal transmission from cockpit to control surface and considering the control surface actuation. Though, the linearised state space model is particularly efficient, all effects of aircraft behaviour cannot be studied solely based on the aircraft dynamics model. In this paper, we aim to develop an integrated model incorporating the actuator model and the pilot model along with the aircraft dynamics. First, PID controller based on Zeigler-Nichols method is developed for the integrated model. Further, the PID parameters are optimized using optimization tool such as Genetic Algorithm. Finally, Fractional Order Controller is also applied to the integrated model. A comparative study of the performance indices of all the three methods is carried out.

Index Terms— Aircrafts,Fractional order controller,Genetic Algorithm, Integrated Model,Non-linear, PID Controller, Zeigler Nichols.

1 Introduction

Aeronautics is one of the most important domains where control plays a major role. Aircrafts flying qualities is necessary and important for safe flight envelope. Aircrafts are never stable by themselves, they need control. Otherwise they would fly in a constant turn. In order to make this aircraft fly in the direction we want, we have to make corrections at any time. There are two ways of making these corrections: the first one is a correction by the pilot, and the other is by automatic flight control system (AFCS) [1]. This AFCS uses a feedback control which is much more accurate and faster, and which can eliminate some disturbances [2].

As we want to study aircraft stability, we have to make a model of the aircraft [3]. The first step for this modelling is to know which equations are used for the flight dynamics. Then we will integrate them in the aircraft model. Most of these equations are nonlinear but we will see that we can get a linear model which is really close from the non-linear model but much easier and faster for simulations. The linearised state space model of the longitudinal dynamics of the aircraft does not accurately represent the actual model of an aircraft system. In actuality, the controller has to take into consideration factors such as pilot delay; Pilot induced oscillations and actuator delay. This poses the need for an integrated model. By introducing a controller we are trying to control the speed of the aircraft along x axis. A transfer function relating the change in elevator angle and Velocity of aircraft along x axis is developed. Controllers are designed for this transfer function.

The main goal of this work is to develop an integrated model for longitudinal dynamics of an aircraft. The Pilot model and Actuator model are combined along with the aircraft dynamics. Finally, Control schemes are implemented for the integrated model and their performance is compared.

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Mathematical model of the integrated model is discussed in Section II. The proposed controllers for the longitudinal dynamics are presented in Section III. Results are presented in section IV. Finally, conclusions are drawn in section V.

II. MATHEMATICAL MODEL OF LONGITUDINAL DYNAMICS OF AIRCRAFT

Dynamic model used for aircraft in this paper are based on Newton's approach [4]. Newton's Second Law of Motion is the heart of equations of motion derivation. These equations explain relationships between forces in the body frame (F_X, F_Y, F_Z) moments (L, M, N) and aircraft linear (u,v,w) and angular (p,q, r) velocities.

$$F_X = m(\dot{u} + qw - rv) \quad (1)$$

$$F_Y = m(\dot{v} + ru - pw) \quad (2)$$

$$F_Z = m(\dot{w} + pv - qw) \quad (3)$$

$$L = I_x\dot{p} - I_{xz}\dot{r} + qr(I_z - I_y) - I_{xz}pq \quad (4)$$

$$M = I_y\dot{q} + rp(I_x - I_z) + I_{xz}(p^2 - r^2) \quad (5)$$

$$N = -I_{xz}\dot{p} + I_z\dot{r} + pq(I_y - I_x) - I_{xz}qr \quad (6)$$

Force and moments can be further broken down into three sub components thrust (created by aircraft engine), gravitational (due to earth gravity) and aerodynamic (produced due to the governing rules of aerodynamics).

Force components due to gravity expressed in body frame can be computed as:

$$(F_X)_{gravity} = -mgsin(\theta) \quad (7)$$

$$(F_Y)_{gravity} = mgcos(\theta)\sin(\phi) \quad (8)$$

$$(F_Y)_{gravity} = mgcos(\theta)\cos(\phi) \quad (9)$$

Force due to aerodynamic is a function of various variables. Let X, Y and Z be the sum of aerodynamic and thrust forces.

$$\mathrm{X} - \mathrm{mgsin}(\theta) = m(\dot{u} + qw - rv) \quad (10)$$

$$\mathrm{Y} + \mathrm{mgcos}(\theta)\sin(\phi) = m(\dot{v} + ru - pw) \quad (11)$$

$$\mathrm{Z} + \mathrm{mgcos}(\theta)\cos(\phi) = m(\dot{w} + pv - qw) \quad (12)$$

Linearised Equations of motion are obtained by applying small perturbation theory to the nonlinear aircraft dynamic equations [5]. In this theory, each variable in the model equations is assumed to have a nominal value (at trimmed flight) plus a disturbance value. The state space model of the aircraft dynamics is obtained as follows:

$$\dot{X} = A\,x + B\,u \quad (13)$$

$$Y = C\,x + D\,u \quad (14)$$

$$A = \begin{pmatrix} X_u & X_w & 0 & -g \\ Z_u & Z_w & U_0 & 0 \\ \tilde{M}_u & \tilde{M}_w & \tilde{M}_q & 0 \\ 0 & 0 & 1 & 0 \end{pmatrix}$$

$$B = \begin{pmatrix} X_{\delta E} & -Xu & -Xw & 0 \\ Z_{\delta E} & Z_{\delta F} & -Z_w & -U_0 \\ \tilde{M}_{\delta E} & \tilde{M}_{\delta F} & -\tilde{M}_w & -\tilde{M}_q \\ 0 & 0 & 0 & -1 \end{pmatrix}$$

$$C = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \quad D = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}$$

$$\dot{x} = \begin{pmatrix} \Delta\dot{u} \\ \Delta\dot{w} \\ \Delta\dot{q} \\ \Delta\dot{v} \end{pmatrix} \quad x = \begin{pmatrix} \Delta u \\ \Delta w \\ \Delta q \\ \Delta v \end{pmatrix} \quad u = \begin{pmatrix} \delta_E \\ u_g \\ w_g \\ q_g \end{pmatrix} \quad y = \begin{pmatrix} \Delta u \\ \Delta w \\ \Delta q \\ \Delta v \end{pmatrix}$$

The State space model is converted into transfer functions; we choose the transfer function relating change in elevator angle and Velocity of aircraft along X axis. Along with this we include the Actuator model:

H(s) = 1/(s+1) (15)

As discussed by [6], Pilot Model transfer function is obtained as:

G(s) = (0.583s+0.001/s+1)*e^{-s}(16)

The transfer function of the integrated model is obtained by multiplying all three transfer functions.

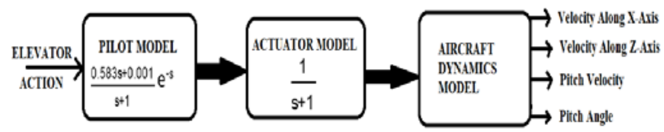

Fig. 1. Proposed aircraft model

TABLE I State space model parameters

Para-meters	**Values**
X_u	-0.014
X_w	0.0043
g	9.8
Zu	-0.0735
Z_w	-0.806
U_0	824.2
M_u	-0.000786
M_q	-0.00051
X_{se}	-0.924
Z_{se}	-34.6
M_{se}	-4.59

III. CONTROLLER DESIGN

1.CONTROLLER TUNING USING ZIEGLER-NICHOLS METHOD

The block diagram of the aircraft system with PID controller is shown in the Figure 2 [7]. The PID controller calculation involves three separate parameters such as proportional, integral and derivative gains. The proportional value determines the reaction of current errors, the integral value determines the reaction based on the sum of recent errors, and derivative value determines the reaction based on the rate at which the error has been changing and the weighted sum of these three terms is used to regulate the process through the final control element.

International Journal of Scientific & Engineering Research Volume 8, Issue 9, September-2017
ISSN 2229-5518

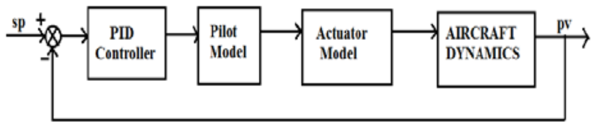

Fig. 2. Aircraft system with PID controller

The PID controller performs better compared to independent operations of P, I and D terms [8]. The selections of gains for the PID controllers are mostly obtained by Ziegler-Nichols method. The gains are determined in terms of two parameters, K_u, called the ultimate gain and T_u, the period of oscillation that occurs at the ultimate gain.

ZN method can also be called as continuous cycling method or ultimate gain tuning method based on sustained oscillations. The gain of the controller is gradually reduced or increased until the system response oscillates continuously after a small external disturbance or step change. A main design criterion is considered as the decay of oscillation to one-fourth of its initial value. The parameters of the controllers can be evaluated using the ultimate gain and frequency values as listed under Table 1. The values of gain K_P, K_I, and K_D can be determined as 2.91, 1.13 and 1.37.

TABLE II Ziegler-Nichols tuning rule

Control Type	K_P	K_I	K_D
P	$K_u/2$	-	-
PI	$K_u/2.2$	$1.2K_P/T_u$	-
PID	$0.6K_u$	$2K_P/T_u$	$K_P*T_u/8$

2. CONTROLLER TUNING USING GA

Genetic Algorithm is a stochastic global adaptive search optimization technique based on the mechanisms of natural selection. GA starts with an initial population containing a number of chromosomes where each one represents a solution of the problem which performance is evaluated by a fitness function [9]. Basically GA consists of three main stages: Selection, Crossover and Mutation [10].

Selection selects the individuals, called parents that contribute to the next generation.
Crossover combines two parents to form children for the next generation.
Mutations apply random changes to individual children.

The application of these three basic operations allows the creation of new individuals which may be better than their parents. This algorithm is repeated for many generations andfinally stops when reaching individuals that represent the optimum solution to the problem.

2.1 Tuning of PID Controller using Genetic Algorithm

The block diagram of the genetic algorithm based PID controller is shown in the Figure 3.

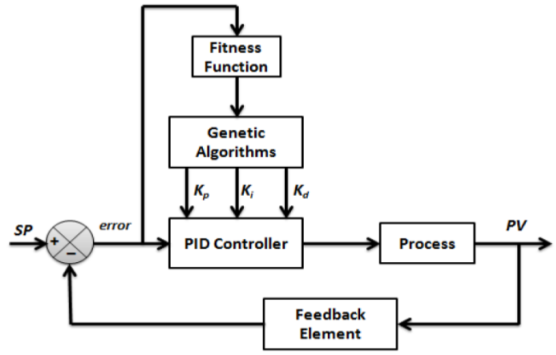

Fig. 3. Genetic algorithm based PID controller structure

The parameters of the Genetic Algorithm used for tuning PID controller are shown in Table II. The optimal values of K_P, K_I and K_D obtained by Genetic Algorithm are 0.7317, 0.8212 and 0.0154 respectively.

TABLE III Parameters of the Genetic Algorithm chosen for tuning PID Controller

Parameters	Values
Number of population	10
Number of generation	50
Number of parameters to be optimized	3
Crossover probability	0.99
Mutation probability	0.01

2.2 Tuning of FOPID Controller using Genetic Algorithm

The fractional-order controller will be represented by fractional-order $PI^{\lambda}D^{\mu}$controller. Where λ and μ are arbitrary real numbers. Taking λ=1 and μ=1, a classical PID controller is obtained. The $PI^{\lambda}D^{\mu}$controller is more flexible and gives an opportunity to better adjust the dynamics of control system [11]. To find out the optimal values of λ and μ, genetic algorithm is used.

The parameters of the Genetic Algorithm used for tuning FOPID controller are shown in Table III. The optimal values of K_P, K_I, K_D, λ and μ obtained by Genetic Algorithm are 0.8235, 0.3816, 0.7655, 0.7952 and 0.1869 respectively.

TABLE IV Parameters of the Genetic Algorithm chosen for tuning FOPID Controller

Parameters	Values
Number of population	10
Number of generation	50
Number of parameters to be optimized	5
Crossover probability	0.99
Mutation probability	0.01

IV. RESULTS

The open loop model response of the integrated model is shown in Fig 4.

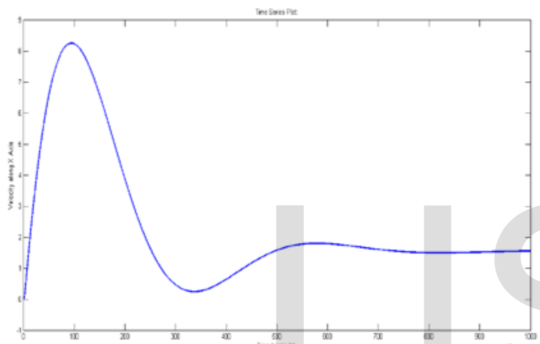

Fig. 4 Open loop response of integrated model

The Servo response of integrated model for Zeigler-Nichols method is shown in Fig 5. Similarly, the servo response of integrated model for GA based PID is shown in Fig 6.

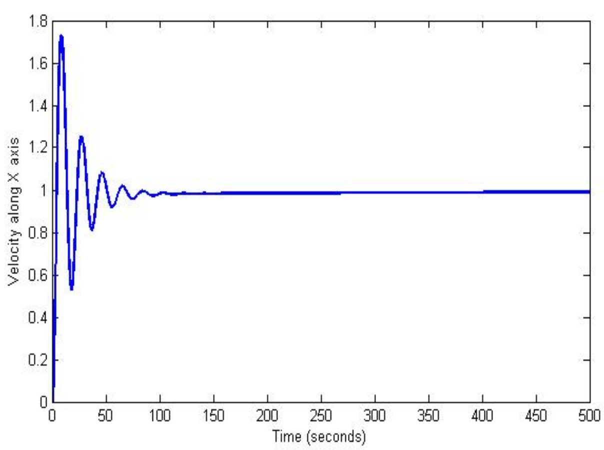

Fig. 5 Servo Response of the integrated model- PID using ZN method

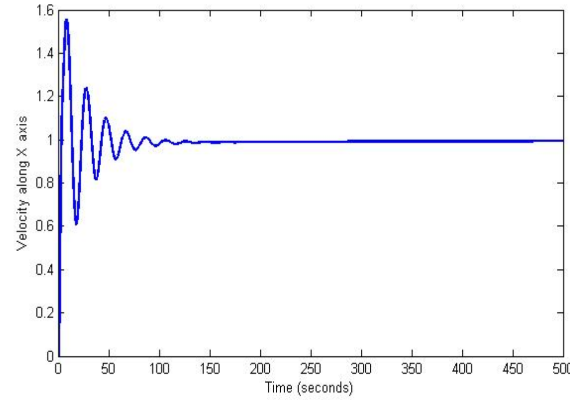

Fig. 6 Servo response of the integrated model with GA based PID

The Servo response of the integrated model for GA based FOPID is shown in Fig 7. On comparison with the other two methods, the servo response of Genetic Algorithm based FOPID is better in terms of reduced overshoots and faster settling time.

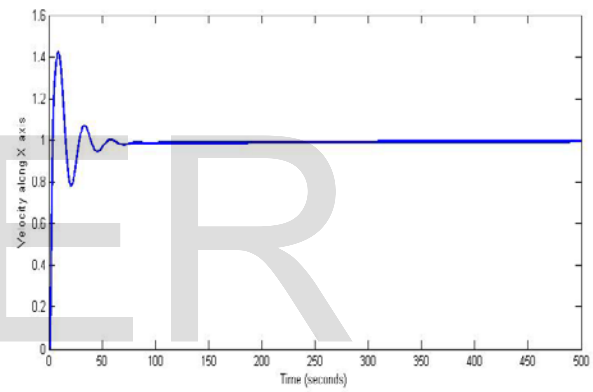

Fig. 7 Servo Response of the integrated model with GA based FOPID Controller

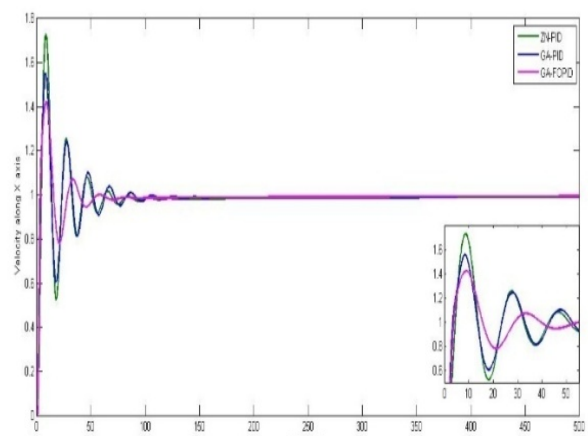

Fig. 8 Comparison of Servo Responses Obtained from Various Control Schemes of the integrated Model

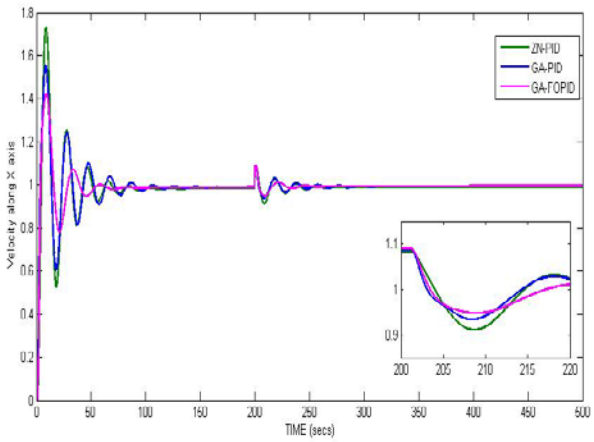

Fig. 9 Comparison of Regulatory Responses Obtained from Various Control Schemes of the integrated model

Comparison of Servo responses of all three methods are shown in Fig 8. The disturbance rejection of all three methods is shown in Fig 9.

The table V clearly depicts that the performance criteria ITAE, IAE and ISE are lower GA based FO PID controller compared to other controllers implemented, thus concluding that GA based FOPID provides better control operation with better performance indices. A set point tracking plot is shown in Figure 10.

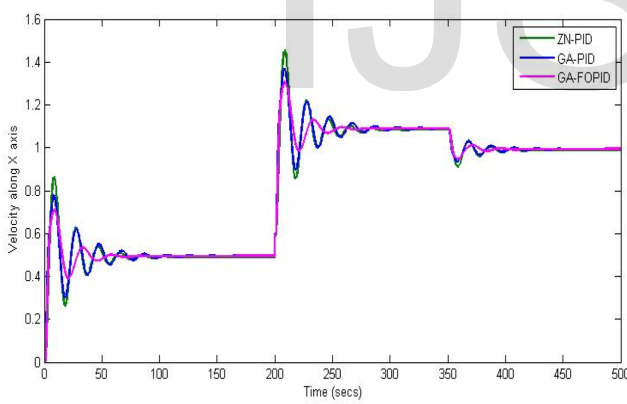

Fig. 10 Response of Set point tracking for various control schemes of the integrated model

TABLE V Comparison of Performance Indices of Various Controllers

METHODS	ITAE	IAE	ISE
GA based tuning (FO-PID)	**1115**	**12.68**	**3.645**
GA based tuning (PID)	1344	16.7	4.827
Zeigler-Nichols tuning(PID)	1830	20.16	6.673

V CONCLUSION

The Integrated model for Longitudinal Dynamics of an Aircraft has been developed. The aircraft dynamics are linearised and then integrated along with the pilot and actuator model. Conventional Controller such as Zeigler Nichols method and optimization techniques such as Genetic algorithm has been applied for PID. Further, Advanced control schemes such as Fractional order PID controller has also been applied. Performance of these controllers is compared with the help of ISE, ITAE and IAE indices. On comparison, it is found that GA based Fractional order PID is better than ZN based PID and GA based PID.

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