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Design and Verification of Carefree Maneuvering Protection for a High-Performance Fighter Aircraft

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ABSTRACT

Flight envelope protection for a high-performance aircraft poses a challenge to the designers and involves a time-consuming procedure to verify the protection. This paper presents a design approach to protect the aircraft from departure by a command path limiter for a rate command attitude hold controller in both the pitch and roll axes. In this approach, the maximum and minimum rates are scheduled as a function of the dynamic pressure on the basis of the open loop aircraft capabilities. This is then augmented with a novel angle of attack protection that comes into play only when the pilot inputs cause the aircraft to exceed the incidence on the positive or negative side (one sided protection), while maintaining the rate command attitude hold behavior within the normal operational bounds of angle of attack. Traditional methods of piloted simulation with a representative cohort of pilots can be time consuming to set up and may not give sufficient confidence whether a departure protection scheme is effective. To address this, a unique multi-modal search using genetic algorithm is developed to verify that this command path protection is able to achieve carefree maneuvering of a fighter aircraft in its entire flight envelope. The sequence of rapid pilot control inputs is coded into a chromosome. The multi-modal genetic algorithm then uses operators like cross-over and mutation on a starting population of chromosomes to evolve new inputs sequences which are then run to obtain the aircraft response. The cost function of the genetic algorithm which is constructed from the aircraft time response is designed to favor the search for multiple maxima which drive the aircraft to departure. The open domain ADMIRE model has been used to demonstrate the approach. Results indicate that the command path design proposed in this paper can be used to protect against departure and the novel multi-modal genetic algorithm helps to verify the departure protection.

Keywords: Carefree maneuvering; Departure verification; High performance fighter aircraft

1. INTRODUCTION

Modern high-performance aircrafts have to operate in high angle-of-attack (AoA) regions of the flight envelope for providing enhanced maneuverability and tactical reasons. An aircraft with a "carefree maneuvering" capability is one which does not exhibit loss of control throughout its entire flight envelope. Departure of an aircraft is normally characterized by an un-commanded motion about any single or multiple axes depending upon the aerodynamic phenomena like flow separation or inertial coupling. Departure is normally precipitated by high rates of rotation or high angles of attack or both. The departure of an aircraft is initiated due to the exceedance of aircraft flight variables like angle of attack or rate of rotation. These regimes are often referred to as "critical flight regimes". Typical critical flight regimes of a fighter aircraft are shown in Fig. 1[1].

Critical regimes can be broadly divided into three major groups based on the aircraft characteristics in these regions namely, region of stall, region of roll coupled rotations and steady state flight regimes like spin (high AoA and roll rates).

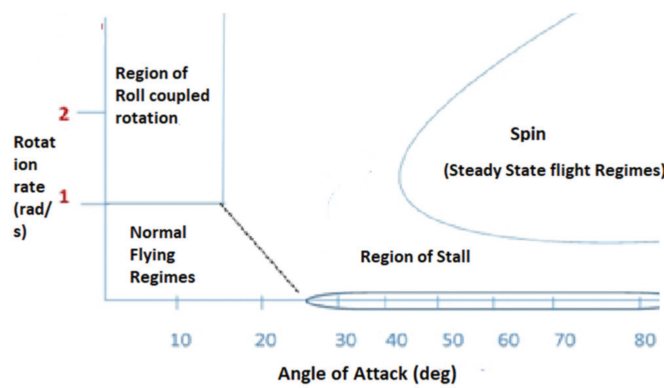

Figure 1. Critical regimes of flight.

During the early years of flight controller design, aircraft designers have developed algebraic criteria based on decoupled, longitudinal and lateral-directional linear dynamic models to indicate the onset of 'departures'[2-6] in terms of the stability and control derivatives. Departure prevention and

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recovery is a real challenge to a flight controller designer. Many control design solutions have emerged to protect from departure[7]. The directional divergence parameter ($C_{n\beta dyn}$) and the Lateral Control Divergence Parameter (LCDP) are the popular algebraic criteria that indicates the lateral / directional divergence. The cross plot of LCDP and $C_{n\beta dyn}$ called Bihrle-Weissman's criteria can predict the departure susceptibility based on the regions demarcated in the cross plot.

2. THE PROBLEM IDENTIFICATION

The cross plot of LCDP and $C_{n\beta dyn}$ for the ADMIRE aircraft used in this study has been plotted in Fig. 2 and it is seen that the aircraft shows a tendency for mild rolling departures (Region 2) at high angles of attack.

As part of further developments, more rigorous tools like Bifurcation theory and Continuation methods were developed to give a deeper in-sight of the flight dynamics problems associated with high AoA and rapid rolls[8-9]. In a real operational environment, for an aircraft with carefree maneuvering capability, large excursions or variations in control input parameters are unavoidable. For fast parameter variations, the aircraft's transient behavior becomes very different from the steady state solutions, as derivatives depending on rates become dominant. Extensive non-linear offline simulations are widely used[10-12] in aerospace research and industry, to test the departure susceptibility of closed loop aircraft dynamics, including all the elements of Flight Control System (FCS).

Modern fighter aircraft are open loop unstable in the pitch axis to enhance agility and performance. This means that their flight control system is highly augmented by closed loop feedback. This can result in adverse interactions between the human pilot and the aircraft dynamics, known as Pilot-In-the-Loop Oscillations (PIO). Many aircraft incidents/ accidents revealed that severe PIO are sudden and unexpected. Generally, before the onset of severe PIO, the aircraft is docile and easily controllable[13]. The main three elements of a PIO are the aircraft, the pilot and the trigger. The trigger could be a non-linear effect in the FCS, a pilot behavioral pattern change, or atmospheric turbulence.

2.1 A Novel Design Solution for Departure Prediction & Protection

A novel Command path limiting scheme suitable for an angle of attack demand system in the pitch axis of a high-performance aircraft has been presented earlier[14-15]. In this research work, the design of the command path for a Rate Command Attitude Hold (RCAH) controller is presented for protection against departure. Numerous dynamic simulations of the aircraft are carried out to test the designed control law effectiveness as well as departure susceptibility of the aircraft. Two existing methods followed are non-linear simulation and Real Time Simulation.

In a nutshell, it would take a large number of simulations to assess completely the departure characteristics of a fighter aircraft in its entire envelope using only the above-mentioned analysis / simulations / PIO analysis. In this paper, we propose an alternate scheme to carry out this evaluation in a shorter time. The proposed method is based on using a Genetic Algorithm (GA)[16-17] to search for possible pilot input sequences which will create departure conditions in the entire flight envelope. The pilot input sequence is discretized into a set of genes. The genes for pitch inputs and roll inputs are then assembled into a chromosome. The genetic algorithm applies operators like cross-over and mutation on the chromosomes to create

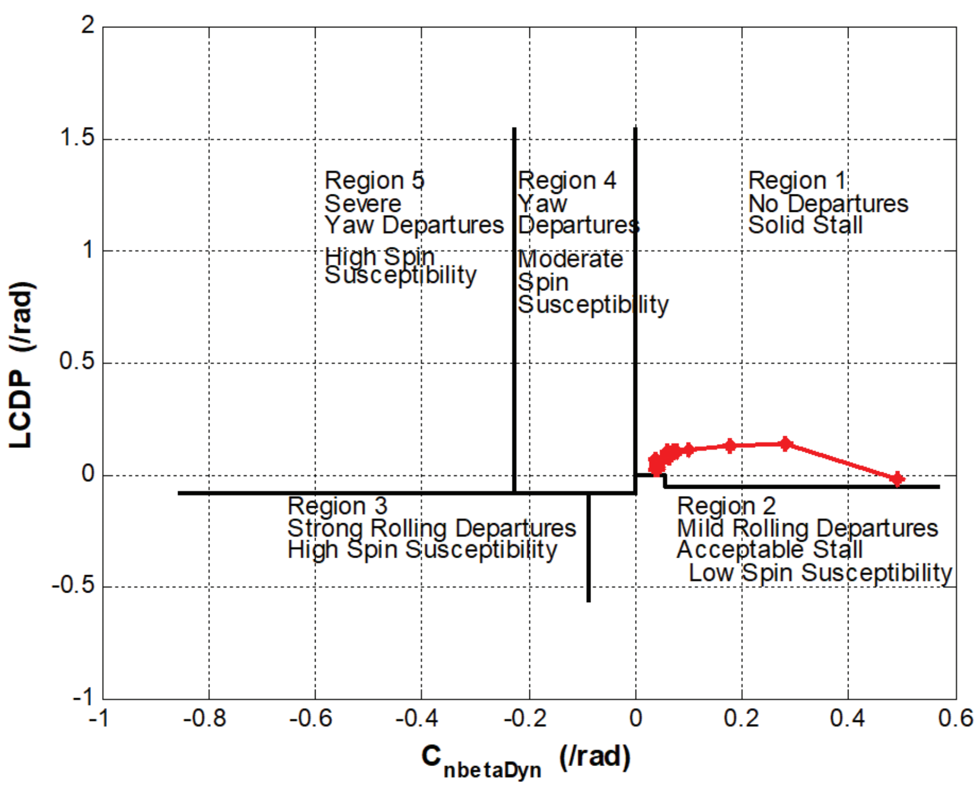

Figure 2. Integrated Bihrle-Weissman's criteria.

another set of pilot input sequences. These sequences are then applied to the flight model of the aircraft and the tendency to depart is calculated based on the time response of the states participating in the short period and Dutch roll modes. GA has been applied to numerous optimization problems related to aeronautical applications[18–22]. A Multi-strategy Adaptive Global Optimization (MAGO) methodology is based on the cooperative sequential gaming between independent players, where the strategies are adopted in each game turn to maximize the cost function. The main objective of this study by Air Defence and Space SAU is to find the global optimum solution[23-26].

In this paper, the conventional GA has been modified to search for multiple departure conditions (multi-modal GA) due to pilot inputs. A novel command path design for a Rate Command Attitude Hold (RCAH) controller against departure and its verification using multi modal Genetic Algorithm (GA) has been presented here. The study has been performed with an open domain aircraft model (complete 6-DoF Simulink model) known as ADMIRE (Aero-Data Model In a Research Environment) simulation model[27]. It is shown that the novel multi-modal GA presented in this paper is able to detect oscillatory departure tendencies which may not be apparent by the use of standard pilot inputs like doublets in pitch and roll axes. The root cause for this oscillatory departure is found to be in the sign of the aileron to rudder interconnect in the original controller in the ADMIRE model. It is shown that once this sign is corrected and the sideslip and its rate feedback gains are tuned to prevent control surface saturation, the ADMIRE aircraft model can be made departure free in the entire flight envelope.

Section 3 presents the departure protection scheme designed for the original ADMIRE simulation model (circa 2006). Section presents the design of a novel multi-modal Genetic search Algorithm. The results of the multi-modal GA based search on the ADMIRE simulation model within its flight envelope are presented in Section 5. Section 6 summarizes the conclusions from the study.

3. DESIGN OF CAREFREE MANEUVERING PROTECTION SCHEME

In this Section, first, the aircraft simulation model used in the studies is described. The departure protection features of the original controller were found to be weak. The modifications of command path to achieve departure protection is explained in the following sub-sections.

3.1 Candidate Aircraft Used in the Study

The aircraft model used for the present study is the ADMIRE (Aero-Data Model In a Research Environment) simulation model[27]. ADMIRE is a nonlinear, 6-DoF simulation model developed by the Swedish Aeronautical Research Institute using the aero data of a generic single seater, single engine fighter aircraft with a delta-canard configuration. This single seat fighter aircraft has multiple pairs of control surfaces. On the wing leading edge, it has flaps on either side. The control surfaces used for the pitch and roll control are called as Elevons and are located at the trailing edge of the wing. Two elevons on either side are provided to increase the redundancy. The forward located canards are all moving type. These control surface pairs can be used together or in a differential mode. The aircraft also has a vertical tail with Rudder (Fig. 3). Though the control surface deflection alters the lift distribution over wing / fin, this effect on aircraft resultant force coefficients is relatively small compare to the moments. Hence these surfaces are used primarily as moment creating devices. The aircraft is equipped with the pitch and yaw control thrust vectoring nozzles which are not considered in this study.

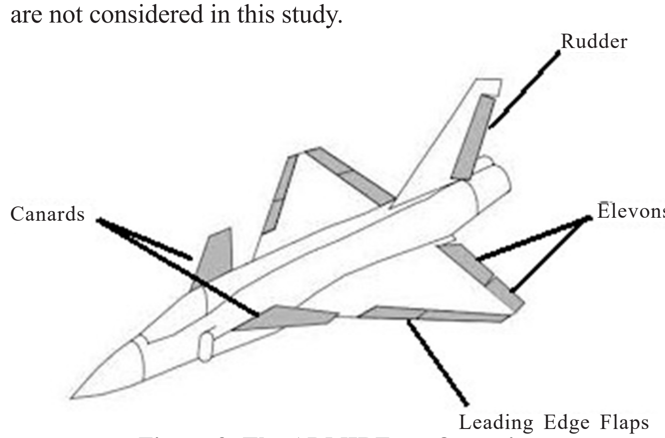

Figure 3. The ADMIRE configuration.

The augmented ADMIRE 6-DoF Simulink model is available with the scheduled gain controller over the entire flight envelope to ensure the robust stability and handling performance[27]. The model also contains saturation and rate limiting blocks along with a nonlinear stick shaping component in the forward path. The controller design has the variables α, β for feedback as the outer loop and pitch rate, stability axis roll rate and yaw rate as the inner loop feedback parameters. The ADMIRE model also includes the engine dynamics and detailed nonlinear actuator models. The baseline controller of the ADMIRE is designed for a velocity vector roll rate of about 180 deg/sec and the maximum operational angle of attack of about 20°.

The original ADMIRE controller (version 4.1, circa 2006) is designed to give RCAH behavior in both pitch and roll axes. It scales the maximum pilot control inputs in the pitch and roll channels of the FCS to the pitch rate demand of 22.8 deg/sec and 180deg/sec respectively. It is possible for the aircraft model to achieve these values at higher speeds (typically the corner speed) in the flight envelope. It was found that the aircraft simulation model is not capable of 1g flight below an equivalent speed of about 90 knots. Thus, at this speed, one expects the maximum commanded pitch rate to drop to zero. Similarly, simulations with maximum roll rate inputs at this speed showed that a roll rate of about 60 deg/sec was possible at low speed while remaining within the control surface limits. Therefore, the first task was to design a command path limiter which correctly captured the open loop limitations of the ADMIRE simulation model. This was then augmented in the pitch channel with an angle of attack limiter to protect against departure while providing the original Rate Command Attitude Hold behavior of the original ADMIRE controller. The original angle of attack protection which came along with the model was found to be inadequate to protect against departures in angle of attack. The

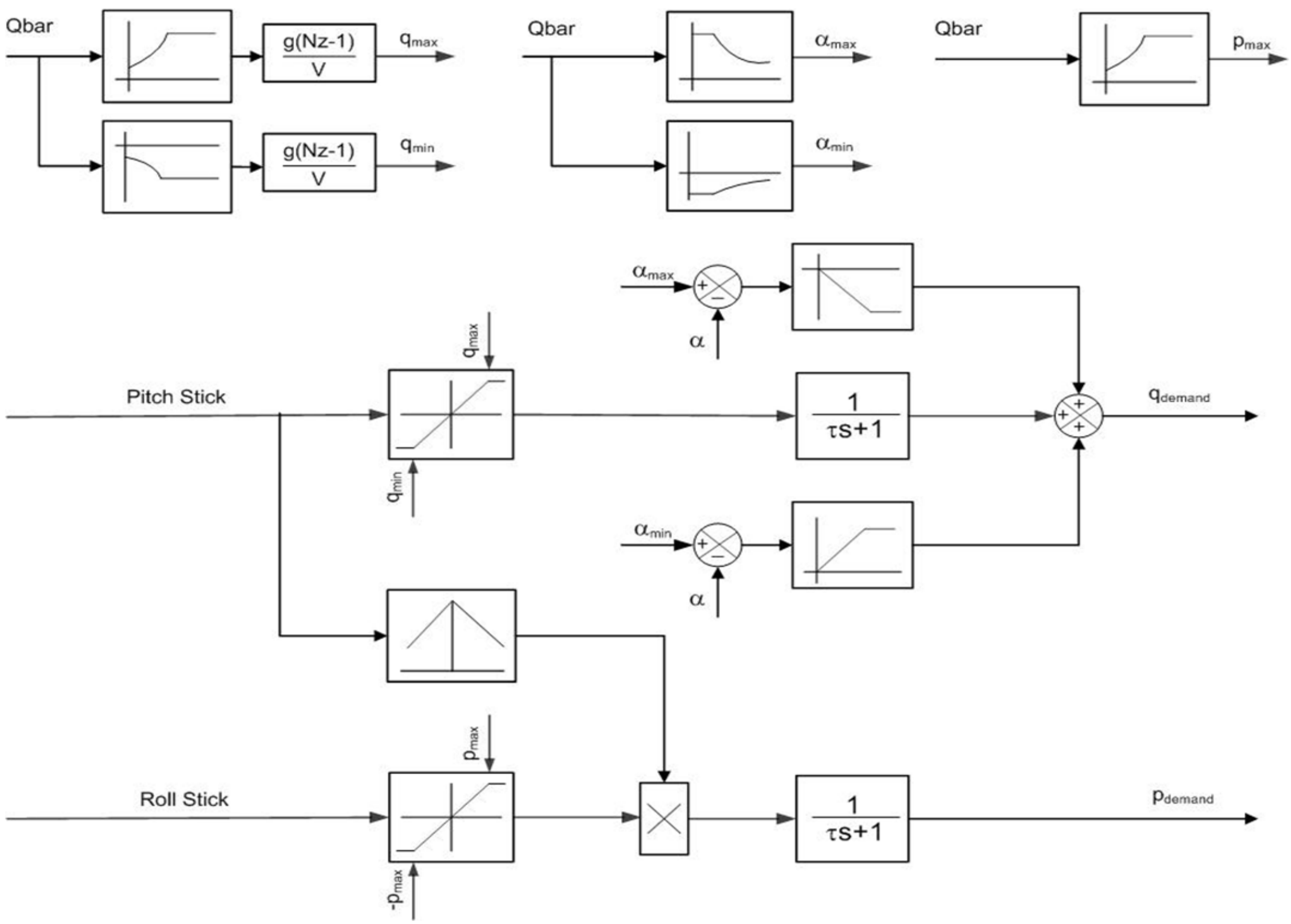

Figure 4. Command path filtering and rate limiting.

modifications in the ADMIRE model to achieve α-Nz demand in the pitch axis has been presented in earlier research work[14-15]. The next section of this paper concentrates on the design of the command path for the original RCAH controller to prevent flight envelope exceedance due to large amplitude rapid pilot inputs.

3.2 Design of the Command Path for Departure Protection

Figure 4 presents the command path scaling for both pitch and roll rates as a function of the dynamic pressure. In case of the pitch axis, the maximum and minimum normal acceleration values in the positive and negative direction respectively are used for computing the respective pitch rates. Similarly, the maximum positive and negative angle of attack is computed and applied via one sided feedback loop, so that a correction is applied only when the angle of attack is exceeded above or below the design values respectively. Further, when combined pitch stick and roll stick inputs are given, a cross channel stick input shaper reduces the peak roll rate demand to half at maximum pitch stick. Finally, a first order filter is applied to the RCAH command in both axes.

In Fig. 5, the response of the aircraft simulation model to simultaneous pitch and roll doublet inputs is shown at a Mach number of 0.7 and altitude of 3000m. This flight condition is chosen as it is approximately at the mid-point of the flight envelope for the ADMIRE and is very close to the corner point where the maximum performance can be expected. It is seen that the response appears to be typical with the aircraft responding to the control inputs in both axes.

The assessment of the FCS is carried out in a similar manner in its flight envelope from Mach number 0.2 to 1.2 and altitude from sea level up to 6000m. In the following section a more efficient multi-model GA search technique is described which is designed to uncover any departure tendencies.

4. DESIGN OF MULTI-MODAL GENETIC ALGORITHM

This section describes the generation of possible short period inputs which can be applied by a pilot to activate the departure conditions by the use of a multi-model Genetic Algorithm search. The initial search is started with a randomly generated set of pilot inputs in pitch, roll and rudder pedals over a period of time (say 10 second). The specific sequence of inputs is stored in the form of a ‘chromosome’. One such set of inputs becomes an ‘individual’ member of a ‘population’.

4.1 Chromosome Definition

Pilot activity involves change or deflection of any or all of the three available control input variables namely, P_{stk}, R_{stk} and R_{ped}. Here P_{stk} corresponds to the deflection of pitch stick, R_{stk} corresponds to the deflection of roll stick, and R_{ped} is the deflection of rudder pedal. Each control input variable is bounded between minimum and maximum value of the pilot

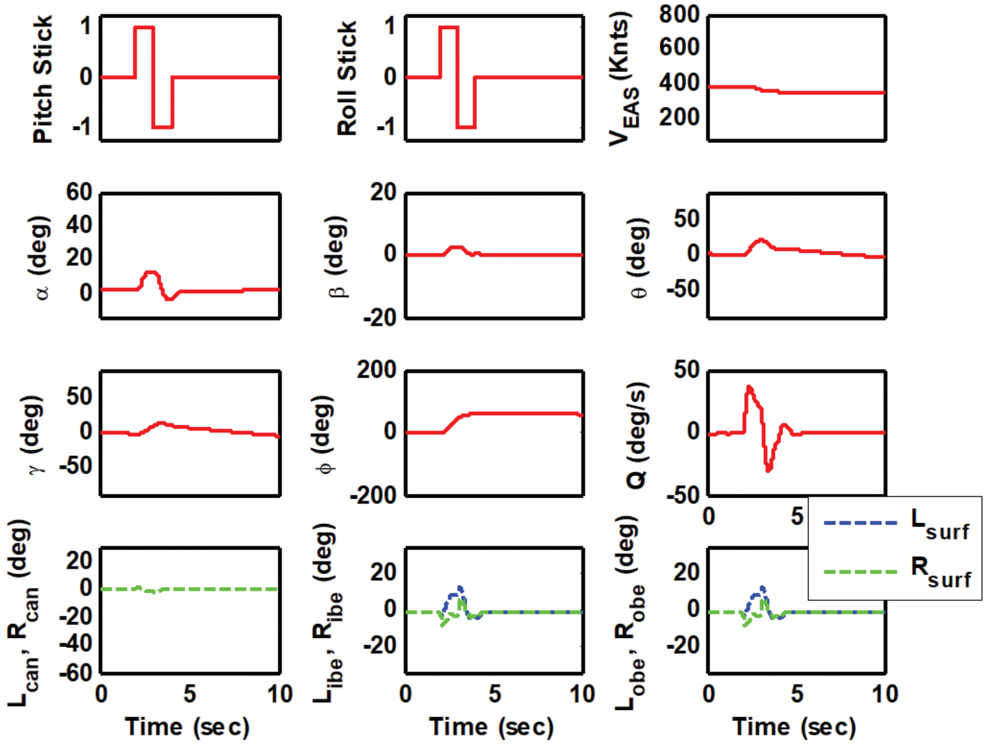

Figure 5. Aircraft parameters for Roll doublet input with initial M=0.7, H=3,000.

inceptor deflections in the cockpit. The stick and pedal limits are given as:

$$P_{stk\,\min} \le P_{stk} \le P_{stk\,\max}$$

$$R_{stk\,\min} \le R_{stk} \le R_{stk\,\max}$$

$$R_{ped\,\min} \le R_{ped} \le R_{ped\,\max}$$

An arbitrary maneuver is represented by a sequence of deflections of control input variables. The sequence of deflections of each control variable is referred as a 'gene'. Thus, any maneuver can be represented by three 'genes' – one gene representing the sequence of pitch stick deflections, second gene representing the sequence of roll stick deflections and the third gene corresponding to rudder pedal. The search is for a sequence of rapid pilot inputs that results in a departure from controlled flight. The chromosome is an element consisting of three genes. The chromosome will also be referred as 'individual / population'.

The short period mode of fighter aircraft is known to occur in the range of 0.6 to 11 rad/sec[15]and can be excited by the fast-varying pitch stick input with a pulse width of about one second. The sequence of one second pulses is assumed to last over about a time period of 5 seconds representing a high gain pilot exercising the flight control system. Similarly, inputs to the roll axis are applied to excite the Dutch roll mode of a typical high-performance fighter which is also in the range of 0.4 to 10.rad/sec[15]. It is expected that this duration of rapid inputs in quick succession in pitch and roll axis of the flight control system is adequate to detect any tendencies for PIO as well as loss of stability or control inherent in the closed loop system. To account for realistic inputs and piloting, a 125 mille sec rise time is taken for changing from the current input level to the next level. Also, the magnitude of the control inputs is limited to half or full of the maximum or minimum possible amplitude.

Table 1. Discretization of bounded control input space for chromosome 'C'

Level	Pitch stick	Roll stick	Rudder pedal
	Range-1 to1	**Range-1 to1**	**Range-1 to1**
0	Full negative	Full negative	Full negative
1	Half negative	Half negative	Half negative
2	0	0	0
3	Half positive	Half positive	Half positive
4	Full positive	Full positive	Full positive

The bounded space of each of the control input variable is discretized into five levels. Table 1 shows the five levels of discretization of the bounded space of control input variable. The control input variable can have any of the 5-levels during every second in the fixed duration of 5 sec. The levels are represented by integers ranging from 0 to 4. An individual, or gene is represented by a sequence of five integers and a chromosome, consisting 3 genes is represented by a sequence of 15 integers, integers falling in the range 0-4. Figure 6 shows representation of a typical chromosome 'C1'. First five integers represent the 'gene1' –the sequence of pitch stick deflection levels, next five integers for 'gene2', corresponding to roll stick and the last five for 'gene3', corresponding to rudder pedal.

A 'gene' of 'Chromosome-C' can have 3125 (5^5) possible combinations in 5-second period of time. Thus, the search space is very large. It has been widely accepted in different

2 1 3 0 3	4 4 3 2 2 1	3 1 4 3
gene1	gene2	gene3

Figure 6. Representation of 'Chromosome C1'.

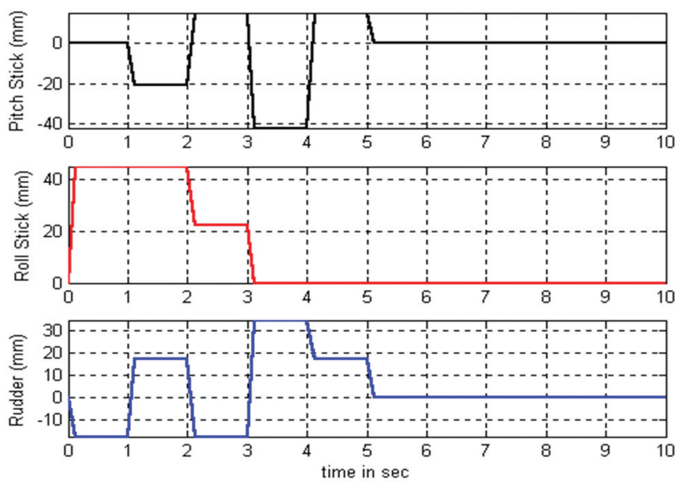

Figure 7. Graphical representation of 'Chromosome C1'.

engineering fields that GA is a robust and global technique that can optimize on a large search space.

Figure 7 shows the chromosome C1 in the form of deflections with respect to time. In the figure, the chromosome information part is only for the first 5-second and next five seconds does not contain any chromosome information (all the inputs are brought to '0').

The chromosome is converted to the sequence of control input deflections in real units by and applied to the aircraft simulation model. The non-linear aircraft simulation model with control law is developed in Simulink. The aircraft is level trimmed at an altitude 'h' meter and an AoA'α' degree. Immediately after the level trim the sequence of control inputs variables are applied for a 5 sec time.

Though the chromosome represents only 5 sec pilot activity, the simulation is continued for another five second with pilot pitch and roll input at neutral, to verify the tendency to depart. The total simulation time is thus for a period of 10 sec.

To begin with at least 10 such 'individuals' are created using a random number generator and this group forms the population for the first 'generation'. Simulations are performed for each member of the first 'generation' to obtain the Fitness function. Here the objective is to find the input which drives the aircraft to departure. The composition and the basis of the 'fitness function' are explained in the subsequent section in more detail.

4.2 Fitness Function

A Fitness function is defined to consolidate the departure information contained in the 10 sec time history. The function is defined as follows:

$$F(t)=\sum_{i}\int_{5}^{10}\left[\frac{\dot{x}_i(t)}{\dot{x}_{i\max}}\right]^2 * dt \qquad (1)$$

where,

t = 1 to 10 sec;

i=1,2,...,5 x={α,β,p,q,r}

Each individual term of the function is the normalized derivative of the states, α, β, p, q and in order to ensure equal weightage for each state variable. It is known that the parameters α, q and β, p, r contribute to the short period and Dutch roll mode respectively. The rates are considered in order to capture the departing characteristics of the aircraft. The terms are squared so that an oscillatory type of divergence will also result in a higher fitness function. Each of the parameters is normalized to bring about uniformity of scale in all the parameters. The $\dot{x}_{\max}$ is the maximum rate of change in the respective state which is obtained from the maximum capability of ADMIRE. Since this search is conducted to bring out the worst-case pilot inputs which induces the aircraft departure, the scaled values of the derivatives of critical parameters are integrated in the fitness function from 5 seconds to 10 seconds (i.e., after the initial period of 5 seconds of rapid succession of inputs is complete).

The maximum rates of change of these five state variables have been arrived at by the following mathematical relations.

$$\dot{\alpha}_{\max} = q_{\max} \qquad (2)$$

$$\dot{\beta}_{\max} = p_{\max}\sin\alpha_0 - r_{\max}\cos\alpha_0 \qquad (3)$$

$$\dot{p}_{\max} = -\frac{C_{l\delta a} * \delta a * \bar{q} * S * b}{I_{xx}} \qquad (4)$$

$$\dot{q}_{\max} = -\frac{C_{m\delta e} * \delta e * \bar{q} * S * C}{I_{yy}} \qquad (5)$$

$$\dot{r}_{\max} = -\frac{C_{n\delta r} * \delta r * \bar{q} * S * b}{I_{zz}} \qquad (6)$$

$$p_{\max} = -\frac{g}{V_0}\sqrt{n^2-1}\,\sin\theta_0 \qquad (7)$$

$$r_{\max} = \frac{g}{V_0}\sqrt{n^2-1}\,\cos\theta_0\,\cos\phi_0 \qquad (8)$$

$$q_{\max} = \frac{g}{V_0}(n-1) \qquad (9)$$

where,

$C_{l\delta a}$, $C_{m\delta e}$ and $C_{n\delta r}$ ate the rolling, pitching and yawing control derivatives respectively.

$\bar{q}$ - Dynamic pressure
S - Wing reference area
b - Wing reference length
C - Mean Aerodynamic Chord
n - Acceleration due to gravity

Ixx, Iyy and Izz are the moment of inertia about x, y and z axis respectively

α_0, θ_0, and ϕ_0 - Trim angle of attack, pitch angle and roll angle respectively

From the Eqns. (2) to (9), the maximum values have been arrived at and the results are given below.

$\dot{p}_{\max}$ = 1170deg/sec^2
$\dot{r}_{\max}$ = 173deg/sec^2
$\dot{q}_{\max}$ = 206deg/sec^2
$\dot{\alpha}_{\max}$ = 30 deg/sec
$\dot{\beta}_{\max}$ = 13 deg/sec

The simulation is carried out for the randomly generated population size of 10. The first generation is then operated upon by the multi-modal GA resulting in the next generation. The populations for the next generation are computed by the process of Crossover and Mutation. The crossover has been done between four pairs randomly chosen from the population in each generation. The crossover operator takes divides each gene at a randomly selected point for each of the parents and crosses then to create a pair of offspring. Mutation is the process of altering the particular gene of a population. Application of these operations on the first 'generation' results in the second 'generation'. The new 'chromosomes' of 'individuals' thus computed are used to construct the Fitness function by simulating the pilot inputs represented by them. Conventional GA algorithms always try to converge to the global optima. In this particular case all of the possible departure solutions are of interest. As opposed to a global optimum, we are searching for the multiple optima. Therefore, it is required to conduct a multi-modal search. The modification to conventional GA to enable multi-modal search is either to have a stable subpopulation and do a local selection in a restricted way, or to have diversity in population by reducing fitness or modifying the fitness landscape (e.g., by de-rating the cost around an existing maxima). In this paper we have avoided the selection process while using cross-over and mutation to create new individuals from the previous population. All the members of each predecessor generation are retained in the final population mix, thereby retaining the population diversity.The process of propagating the generations is continued up to the generation where the maximum value of the Fitness function within the population does not increase significantly and appears to converge asymptotically to a value.

For a particular generation, the minimum and maximum fitness function value has been calculated. The simulation is continued till the maximum fitness converges to a value. From the study it is observed that around 50 generations of propagation are adequate to reach a best fitness function. The number of generations can be increased in case the convergence is not achieved within 50 generations. The simulation is repeated for each Mach number to detect departures in the flight envelope.

5. VERIFICATION OF DEPARTURE PROTECTION

In this Section, the results of scanning the entire flight envelope using multi-modal GA are discussed first. This is followed by an analysis of the reasons for the departure seen in the original ADMIRE controller. Finally, once the controller is re-tuned correctly, the GA is run again and the resulting controller is shown to be departure free in the entire flight envelope.

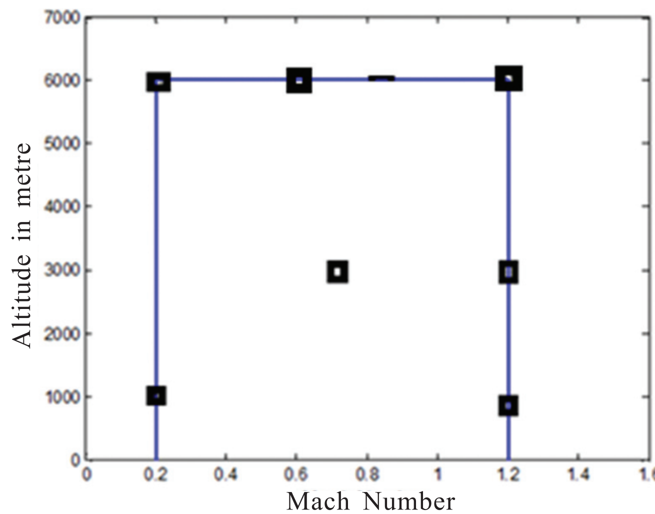

Figure 8. Typical ADMIRE flight envelope with the simulation flight conditions.

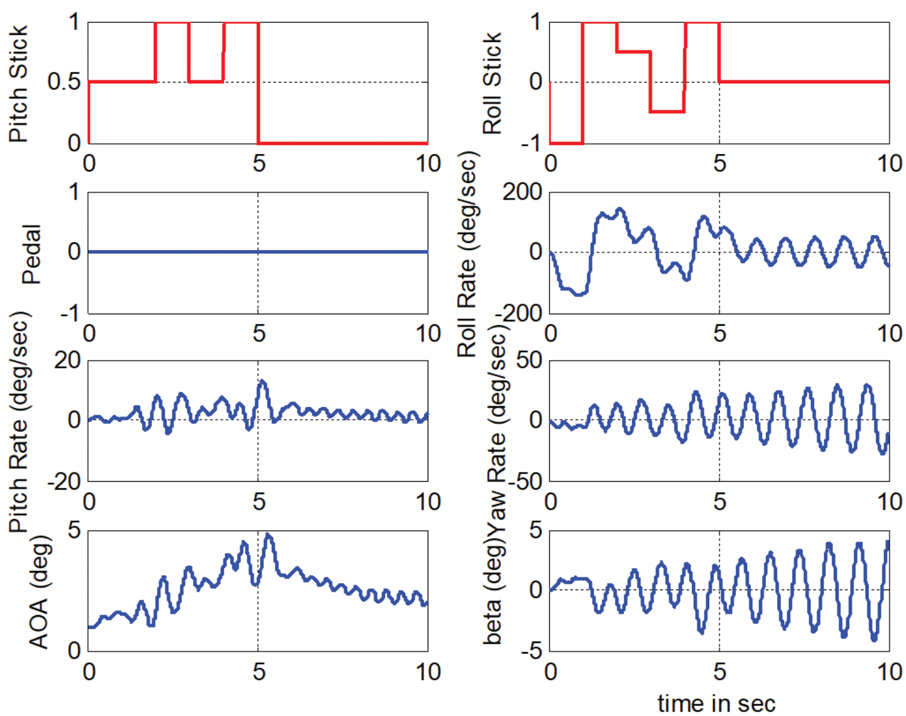

Figure 9. Variation of aircraft parameters with initial M=1.2, H= 6,000 m.

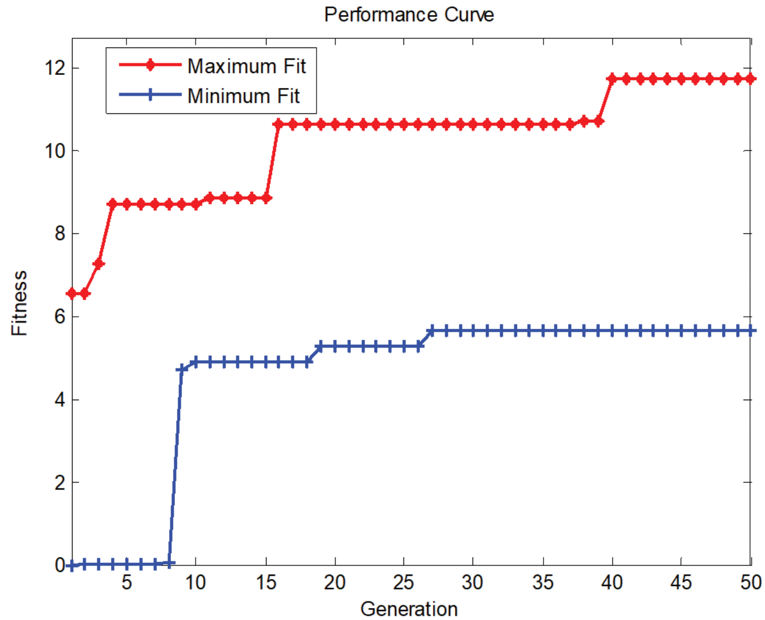

Figure 10. Variation of fitness function with initial M=1.2, H= 6,000 m.

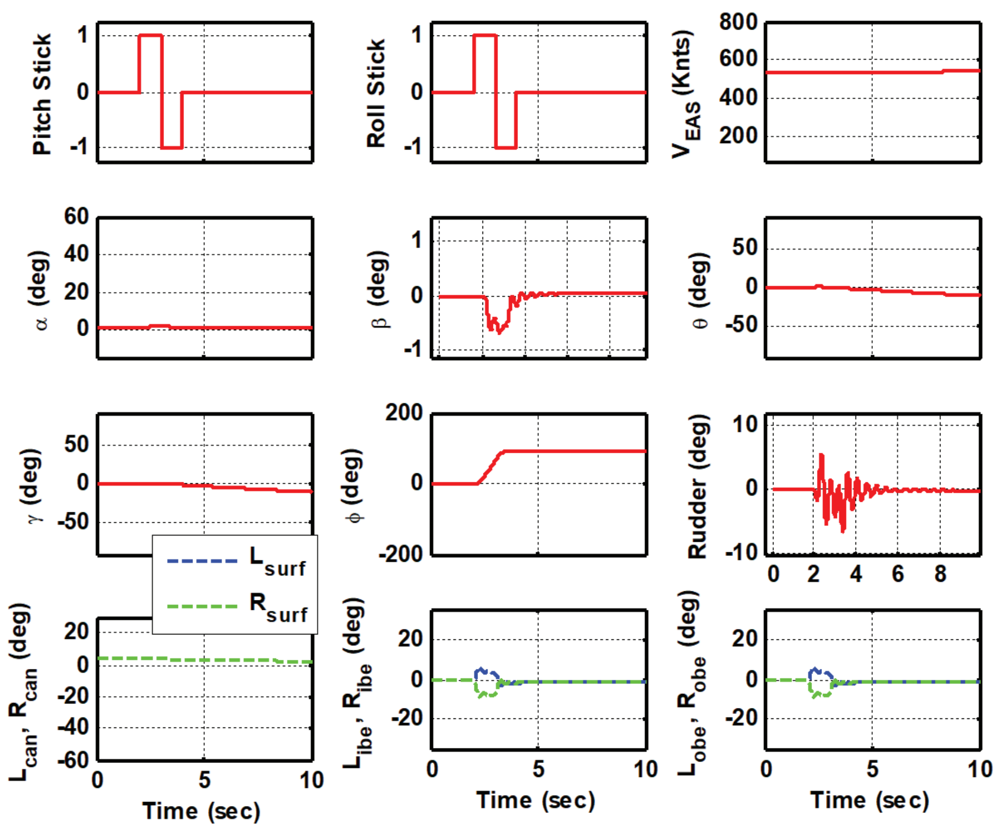

Figure 11. Aircraft parameters for Roll doublet input with initial M=1.2, H=6,000 m.

Since the ADMIRE controller is designed to create velocity vector roll by feeding back estimates of sideslip and its rate of change to the rudder, the rudder pedal inputs are not considered as pilot inputs for the simulation. The pitch and roll axis inputs are used simultaneously to test the closed loop controller. The ADMIRE flight envelope is shown in the Fig. 8.

The flight envelope spans Mach numbers from 0.2 to 1.2 and altitude from 1000m to 6000m.For all the conditions marked by a square in Fig. 8, departure characteristics have been studied and are given in the supplementary material. The results of the flight condition given below are discussed further here.

M= 1.2; H=6000m

The aircraft response for the input history generated by the multi-modal GA which gives the maximum fitness value and the respective fitness function plot for the above case are given in Fig. 9 and Fig. 10 respectively.

Figure 9 presents the simulation results for the maximum fitness condition at the right-hand corner of the flight envelope. Results show that there is an oscillatory marginally unstable mode which has got excited and the aircraft is being driven to departure. Though the values of α and β are low, the values of p, q and rare high. The maximum Fitness function is around 12 due to the oscillatory trend of the parameters p, q and r as shown in Fig. 10.

These oscillatory conditions were found to occur in the upper right-hand quadrant, namely for altitudes more than 3000 m and Mach>0.6.

As we seen from Eqn. (1), the Fitness function is the algebraic some of the squares of the normalized $\dot{\alpha},\dot{\beta},\dot{p},\dot{q},\dot{r}$. For low Mach number (M<0.7) cases the fitness values are low due to its low manoeuvring potentials (low p, q, r). On the other hand, at the flight conditions of M>0.9, though the manoeuvring capability is relatively high, the values of α and β are low. The flight condition M=0.7 and H=3000 m, which is around the centre of the flight envelope shows the maximum manoeuvring capability with the reasonably high value of α and β. Thus, the Fitness function is high in the middle part of the flight envelope when compared to other flight conditions.

In order to verify the plant characteristics for standard inputs, the roll doublet and combined roll and pitch doublet inputs were given and the aircraft parameters are verified. The Fig. 11 shows results for M=1.2 & H= 6000 m. It is observed that although oscillatory behaviour is seen in the rudder response, it does damp out within a few oscillations. Thus, those non-linear simulations where only the specific synthetic inputs like, step, doublet, 3-2-1-1 etc. are applied, could not completely bring out the divergent nature of the plant. In the other hand subjecting the simulation model to the multi-modal GA did result in highlighting these tendencies mainly because, the GA created a series of multiple rapid inputs which maximized the tendency for departure.

The highly oscillatory tendency of the lateral / directional parameters could be due to the surface rate saturation or due to improper tuning of the control law gains. Since the oscillations are in the β and rudder surface, the gains in the β-path and the Aileron Rudder Interconnect (ARI) gain in the original ADMIRE FCS model were examined. The initial ARI gain is -1. This value has been varied and found that at the value of '+1' the oscillation is stopped and the side slip developed at various flight conditions are <5 deg for doublet inputs. At low mach numbers and altitudes (M=0.2, H= 1000 m), it is observed that the rudder is saturating for a short duration for the roll doublet input. Hence the gain in the β- path (both sideslip and its rate) has been reduced by half.

To confirm the effect of the change in the control gains, the GA simulations have been carried out for all the critical points of the ADMIRE flight envelope. It is confirmed that there are no oscillations found in the entire flight envelope. The GA results for M=1.2, H=6000 m is shown in Fig. 12 and Fig. 13.

From Fig. 12 it is seen that the aircraft response parameters α, β, p, q and r and control surfaces show a stable tendency and the rate of reduction is low. Though the value of roll rate is high,

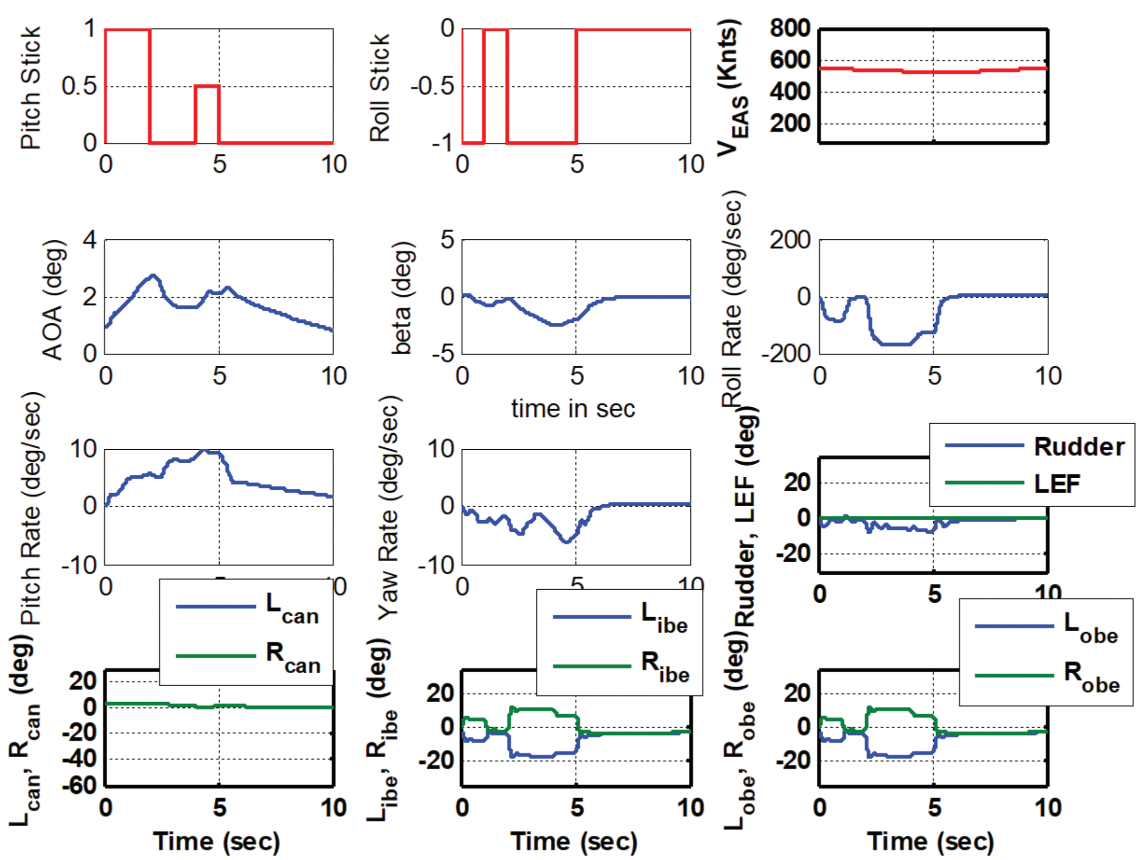

Figure 12. Variation of Aircraft Parameters with initial M=1.2, H=6,000 m.

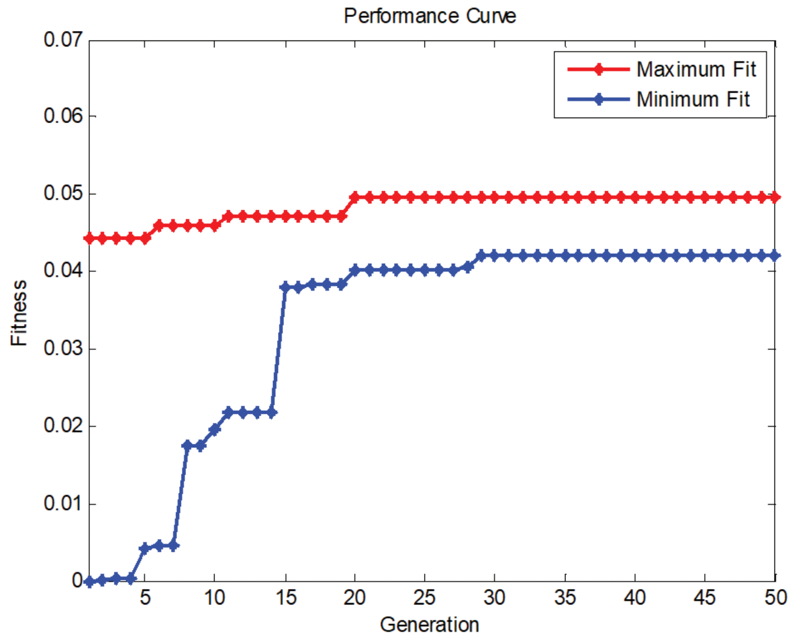

Figure 13. Variation of fitness function with initial M=1.2, H=6,000 m.

the α, q, r and β values are low. The maximum Fitness function is around 0.05 as shown in Fig. 13.

The results conclusively prove that the multi-modal GA designed in this paper is able to search for and bring out any latent tendencies within a control system to depart from controlled flight.

6. CONCLUSIONS

A command path design for the RCAH controller of the ADMIRE aircraft simulation model is proposed to prevent departure from controlled flight. A specially designed multi-modal GA based search is employed to verify whether the command path protection is able to prevent any departure tendency. At some of the flight conditions the aircraft parameters are oscillatory which could not be predicted by the simulations using standard inputs like simultaneous doublets in pitch and roll axis. Thus, the results establish the value of the proposed multi-modal GA to successfully detect departure tendencies.

The root cause for the oscillation of the lateral / directional parameters have been found to be linked to the β-path and ARI gains (yaw axis). The ARI gain and gains for the sideslip and slideslip rate feedback for the ADMIRE controller were tuned and the multi-modal GA search was run again. The proposed design solution for the command path was found to be effective in protecting the aircraft from the departure.

This methodology of analyzing the departure characteristics of a multirole fighter aircraft for a numerous pilot inputs are humanly impossible. The GA based algorithm can be used effectively for the prediction of latent departure tendencies for any fighter aircraft. Subsequently, detailed analysis can be used for the clearance of flight control law for the flight testing.

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