# Symbolic control approach to aircraft taking off in wind shear

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**Abstract**
**Purpose** – The purpose of this paper is to propose an approach for aircraft taking off control in wind shear, which is a challenging issue for an aircraft.
**Design/methodology/approach** – Aircraft control in wind shear needs an anti-jamming controller. Symbolic control is an effective and adaptive method for complex dynamic system. In this paper, wind shear flight control laws are developed for the dynamics of a B-747 aircraft by using symbolic control. The problem of efficiently steering dynamical systems with disturbance by using symbolic control is considered, and theoretical analysis on the proposed approach is also conducted. The implementation of an altitude scheduling strategy with symbolic controller makes it possible for aircraft to escape serious wind shear.
**Findings** – This work improved symbolic control algorithm so that it can be applied to aircraft control problem. A series of comparative experimental results with proportional-integral-derivative controller demonstrate the feasibility and effectiveness of the proposed approach.
**Practical implications** – The symbolic control method developed in this paper can be easily applied to another aircraft control problems.
**Originality/value** – An improved symbolic control method is proposed for solving aircraft taking off problem in wind shear.

**Keywords** Aircraft, Symbolic control, Takeoff, Wind shear, Flight control

**Paper type** Research paper



## Introduction

Wind shear is an important and critical influence on the landing of an aircraft. More than 40 per cent fatalities were caused by low-attitude wind shear, and all the civil aviation accidents occurred under an attitude of 300 m. Microburst is a kind of strong localized downdraft that strikes the ground, which create winds that diverge radically from the impact point. The problem of quantitatively defining the effect of wind shear with given magnitude on an aircraft during descent has been completely resolved, and it has been found that effective recovery from wind shear encounters require unusual piloting techniques.

Over the past decades, numerous approaches have been developed for flight control in wind shear. There exist many approaches for flight simulation in wind shear (Sontag, 1995), but there are still many problems in control. Before the 1990s, linearization method is still the main control method, either in manual or automatic wind shear measurement. When the dynamic inversion method nonlinear inversion dynamics becomes mature and successful (Sontag, 1995), researchers can establish more reasonable responses to wind shear. The symbolic control is a novel method to solve the problem of planning inputs to steer a controllable dynamical system. In the control literature, methods for the generation of reference trajectories have been considered as feed-forward components in a 2 df controller design (Nieuwstadt and Murray, 1998). In this spirit, several researchers have changed the problem by reducing the observation matrix dimension. Several contributions have appeared in recent years that address different instances of symbolic control problems (Egerstedt and Brockett, 2003). The key factor of symbolic control is that system feedback can substantially reduce the specification complexity to reach a certain target state.

This work mainly focuses on finding a simple, effective and robust control approach under the complicated wind shear. For most of the existing approaches like proportional-integral-derivative (PID) and linear-quadratic regulator (LQR) methods (Zhang and Duan, 2013), it is difficult to satisfy both the control performance and the solving difficulty simultaneously. To overcome the drawback of these traditional approaches, the approach of symbolic control is used here. In this paper, a symbolic control method is used to solve the aircraft control problem. A symbolic encoding scheme is used to ensure that the control actions on the system have the desirable properties of additive groups.

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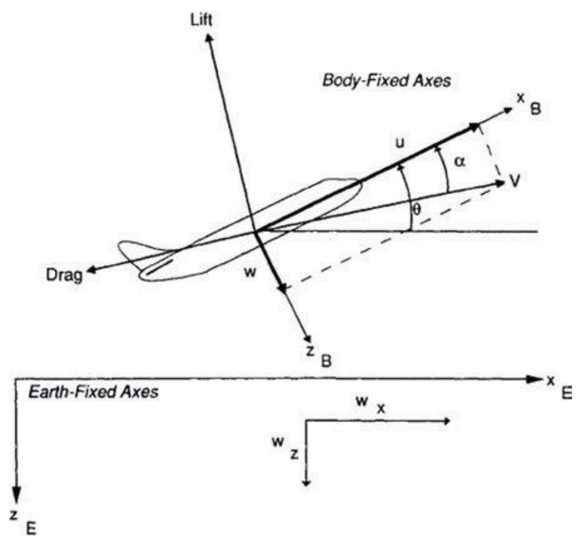
Furthermore, under the action of words in the symbolic language, the reachable set becomes a lattice. Finite-length plans to steer the system from any initial state to any final state within a given region can thus be computed in polynomial time (Egerstedt and Brockett, 2003). We also proved that for a controllable linear discrete-time system of aircraft, there exists an integer and a linear feedback encoding, such that there exists a quantized control set for all subsequences of period during flight. We present a flight control problem for a B-747 encounters with microburst on final approach (Tomczyk, 2008). The objective of this work is to design a flight controller, which can maintain an adequate stall margin during the climb out.

The rest of this paper is organized as follows: the effect of wind shear on aircraft dynamics is introduced next. Subsequently, the basic definition and theory of symbolic control are given. Then, we propose an approach for applying symbolic control to aircraft taking off control in wind shear, and theoretical analysis on the proposed method is also given. The comparative simulation results with PID controller are given to verify the feasibility and effectiveness of the proposed hybrid approach for aircraft next. Our concluding remarks are contained in the final section.

## Equations of motion and aircraft model

The effect of wind shear on aircraft is reflected as complex nonlinear functions of plane parameters: mach number, altitude, rotation rates, angles of attack, control surfaces, thrust changes and flap setting. A 3 df model of a B-747 aircraft is used in this paper. The aircraft's operating empty weight is 415,000 lb, and its maximum takeoff thrust is 243,000 lb. Effects of wind shear on aircraft motion and aerodynamics are modeled according to the existing research (Hanke, 1971). Figure 1 shows the relevant reference coordinate system used to describe the aircraft's velocity, direction and position. We assume that the plane is flying in a vertical plane over a flat earth, and a ground-fixed coordinate system is defined as the inertial reference frame. According to these general assumptions, the motion equations are as follows:

**Figure 1** Coordinate system and reference frames




$$\dot{x} = V\cos\gamma + w_x \tag{1}$$

$$\dot{z} = V\sin\gamma - w_z \tag{2}$$

$$\dot{V} = \frac{T}{m}\cos\alpha - \frac{D}{m} - g\sin\gamma - \dot{w}_x\cos\gamma + \dot{w}_z\sin\gamma \tag{3}$$

$$\dot{\gamma} = \frac{1}{V}\left(\frac{T}{m}\sin\alpha + \frac{L}{m} - g\cos\gamma + \dot{w}_z\cos\gamma + \dot{w}_x\sin\gamma\right) \tag{4}$$

$$\dot{\alpha} = q - \dot{\gamma} \tag{5}$$

$$\dot{q} = M/I_{yy} \tag{6}$$

where, $\alpha$ and $\gamma$ represent the angle of attack and flight-path angle, respectively. $W_x$, $W_z$ are wind components along the $x$ and $h$ axes, respectively. $V$ is the airspeed. $x$ denotes the position expressed in an earth-fixed coordinate system, while $z$ is the altitude. $I_{yy}$ represents the moment of inertia. $q$ is the body-axis pitch rate. $M$ is the pitching moment. $L$, $D$ and $T$ are the lift, drag and engine thrust, respectively. $g$ is the gravity acceleration, and $m$ is the mass of the aircraft.

The equations that define the aerodynamic forces and moments and the equations of the control surfaces are added. The lift, drag, pitching moment and thrust are expressed as follows:

$$L = \bar{q}\, S_{ref}\, C_L \tag{7}$$

$$D = \bar{q}\, S_{ref}\, C_D \tag{8}$$

$$T = T_{\max}(V_a)\delta_T \quad 0 \le \delta_T \le 1 \tag{9}$$

$$M = \bar{q}\, S_{ref}\, \bar{c}\, C_M \tag{10}$$

where, $\delta_T$ is throttle setting. $S_{ref}$, $C_L$ and $C_D$ are parameters of B-747 aerodynamic derivatives. The Oseguera – Bowles downburst model research provides a typical wind components and spatial gradients model that can be used in standard equations of motion (Oseguera and Bowles, 1988). This analytic model represents an axisymmetric stagnation point flow, based on wind velocity profiles from the Terminal Area Simulation System. The model satisfies continuity in cylindrical coordinates, and the wind components closely match real-world measurements, as do the increase, peak and decay of outflow and downflow with distance from the microburst core.

In this paper, we use symbolic control as a linear method. We use symbolic math toolbox in MATLAB to get linear equations. The toolbox can give symbolic expression of liner equations. The steps are:

- *Step 1*. Establish non-linear model by programming an M-file, define the states and control inputs, wind interference as inputs and derivative of the states as outputs.
- *Step 2*. Define the states and control inputs, and wind disturbance as the symbols with the "syms" command.

Then use the non-linear model in Step 1 to calculate the symbolic expressions of derivative of each states; using the "Jacobian" command, calculate Jacobian matrix which relate derivative of each states to the states to get dynamic A. We can get dynamic $B$ as same.

- *Step 3*. Use needed equilibrium point of states and control inputs, and wind disturbance into the dynamic A and $B$, we finally get symbolic expression of liner equations.

## Symbolic control

Based on a finite number of inputs, symbolic control can steer dynamic system from one state to another. A finite or countable set $U$ of control quanta can be encoded by associating its elements with symbols in a finite set $\sum = \{\sigma_1, \sigma_2, \ldots\}$. Furthermore, letters from the $\Sigma$ can be used to build words of arbitrary length. Including the empty one, we get $\sum *$ be the set of such strings.

Hence, in proper input coordinates and initial state, the dynamics system can be written as (Bicchi *et al.*, 2006):

$$z^{+} = z + H\mu, H \in R^{n \times n}, \mu \in Z^{n} \tag{11}$$

**Definition 1:**
By defining a map $\varphi_{(u,\,T)}: X \rightarrow X$, a control quantum can be expressed as $(u, T)$, such that at time $T(x_0)$, $x_0 \in X$, $\varphi_{(u,\,T)}(t)$ is given as the solution of the equations formed in time domain:

$$\begin{cases} \dot{x} = f(x, u_t(\tau, x)) \\ x(0) = x_0 \end{cases} \tag{12}$$

Symbolic control scheme is solved by calculate the state space transform matrix $T$ and control inputs $U = \{u1, u2, u3, \cdots, u_N\}$. Symbolic control also need symbolic encoding includes state feedback and symbols and control inputs transformation.

A few examples of possible control encoding schemes of increasing generality are pictorially described in Figure 2.

In *piecewise constant encoding*, there is a one-to-one correspondence between input symbol $\Omega$ and a control quantum $q_i(u_i, T)$, and $u_i$ is a time constant associated with $T_i$ (Figure 2a). In this encoding structure, we use input quantization, which is defined in some part of the literature. In general systems, the form of piecewise constant inputs is specially built unstructured. However, when reasonable piecewise-constant control quanta is added, the special class of chained-form driftless systems is changed to a approachable form.

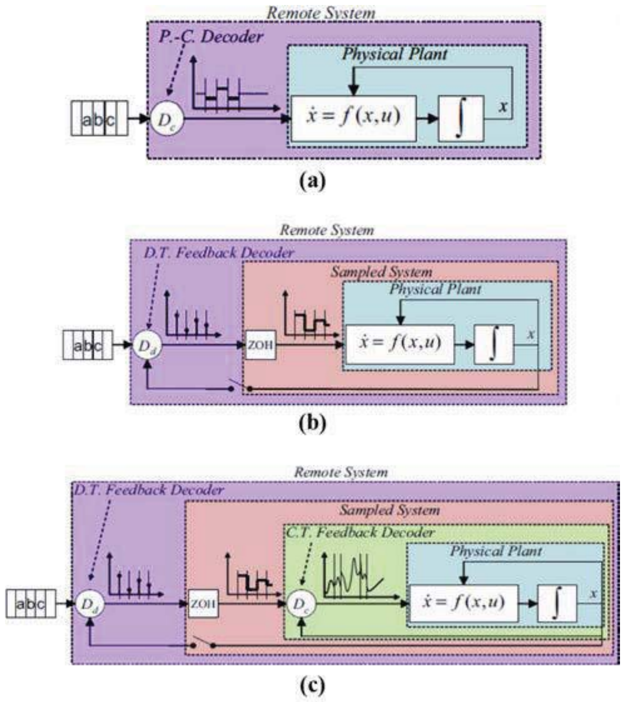
### Piecewise smooth encoding

In this encoding structure, the system state do not affect $u_i$, which is composed by smooth functions of time, and $T_i$ is fixed (Figure 2b). This structure may allow for more effective planning. For instance, in an approximate optimal control planning, calculate $u_i$ as different parts of extremal controls inputs to steer the system.

### Feedback encoding

The symbol itself, the symbol structure and the current state of the system codetermines a control input $u_i$ By defining a feedback $u = f(x, r)$ added on system (12), and a piecewise constant encoding on the reference, the system can be realized either directly in continuous time (Figure 2b), or indirectly through sampling (Figure 2c).

**Figure 2** Three examples of symbolic encoding of control. As inputs of the system, symbols (represented by letters) pass through the finite-capacity channel




**Notes:** (a) Piecewise constant encoding; (b) discrete-time feedback encoding; (c) nested discrete-time continuous-time feedback encoding

Attributed to previous efforts of others, now provide a very efficient method to steer a dynamic system from arbitrary original state $x$ to a given goal state $x + \delta$ within an $\varepsilon$-neighborhood (Bicchi *et al.*, 2002):

- *Step 1*: Without loss of generality, assume that the system initial state is 0, define the goal state $\delta$ in original coordinate system. Calculate the desired displacement in Brunovsky coordinates and get system state increment $\Delta = S^{-1}\delta$, and let $\Delta_i \in R^{ki}$, $r = 1, 2, \cdots, r$, represent the wanted displacement for the $i$ th subsystem.
- *Step 2*: Calculate the lattice mesh size in Brunovsky coordinates $\gamma_i = 2e/\|\xi_i\|$, where:

$$[\xi_1 \quad \xi_2 \quad \vdots \quad \xi_r] = \begin{bmatrix} 1_{k1} & 0 & \cdots & 0 \\ 0 & 1_{k2} & \cdots & 0 \\ \vdots & 0 & \ddots & \vdots \\ 0 & 0 & \cdots & 1_{kr} \end{bmatrix}$$

- *Step 3*: Find $\overline{\Delta}_i$, the nearest point to $\Delta_i$ measured by the lattice, which is generated by $\gamma_i W^i$ and its range to $\xi_i = (S^{-1}x)$ not more than $e$.
- *Step 4*: For each $i = 1, 2, \cdots, r$, set the quantized control as $W^i = \{0, \pm\omega_1^i, \cdots, \pm\omega_{m_i}^i\}$, $\omega_j^i \in N$, and denote by $U^i$ the vector $[\omega_1^i, \omega_2^i \cdots, \omega_{m_i}^i]$, where $\omega_0^i = 0$. Write $\overline{\Delta}_i = \gamma_i C^i U^i$, where $C^i \in Z^{ki \times m_i+1}$ with components

$c^i_{h,j}, j = 1, \cdots, m_k + 1$. Then decode plan specifications $C$ into a string of control inputs $V$.

## Symbolic control based taking off control law design

**Theorem 1:**
For a controllable linear discrete-time system of aircraft $x^+ = Ax + Bu$, there exist an integer $\ell > 1$ and a linear feedback encoding

$$E: \begin{matrix} \Omega \rightarrow U \\ \sigma_i \mapsto Kx + \omega_i \end{matrix}$$

With constant $K \in R^{n \times n}$ and $\omega_i \in W$, $W \subset R^r$, a quantized control set, such that, for all subsequences of period $\ell T$ extracted from $x(\bullet)$, the reachable set is a lattice of arbitrarily fine mesh. In other terms, for $z(k) = x(\tau + k\ell)$, $\tau, k \in N$, it holds

$$z^+ = z + \overline{H}\mu, \overline{H} \in R^{n \times n}, \mu \in Z^n$$

And for every $e$, there exists a choice of a finite $W$ such that $\|\overline{H}\| < e$.

And in case there is a disturbance input, if we choose several control steps forward from $W$ as $\overline{W}$, as the system control input within $\overline{\ell T} < \ell T$ ($\overline{\ell T}$ should be short enough), and update feedback encoding after every $\overline{\ell T}$, after $n\overline{\ell T}$ ($n$ is a finite integer), the system reachable set will be a lattice finally.

**Proof:**
For every $e$, there exists a choice of a finite $W$ such that $\|\overline{H}\| < e$.

Consider the situation with disturbance input. Choose several control steps forward from $W$ as $\overline{W}_1$, as the system control input within $\overline{\ell T} < \ell T$. After the first $\overline{\ell T}$, the deviation between system states and expected system states is . $\overline{\varepsilon}_1$Then we update the feedback encoding, get the second control input $\overline{W}_2$, then we repeat the step above. After the second $\overline{\ell T}$, the deviation becomes $\overline{\varepsilon}_2$, obviously $\overline{\varepsilon}_2 < \overline{\varepsilon}_1$. After several $\overline{\ell T}$, the $\overline{\varepsilon}_n$ is quite small. If $\overline{\ell T}$ is short enough, it can be smaller than $\varepsilon$ with disturbance input.

Firstly, we can obtain dynamics A and B from nonlinear equations by using symbolic math toolbox in MATLAB. We use longitudinal aircraft dynamics A and B to design symbolic control laws.

The states are airspeed, angle of attack, pitch angle and pitch rate $[\Delta V\, \Delta\alpha\, \Delta\theta\, \Delta q]$, and the input is elevator $\delta_e$ and throttle $\delta_T$. The equilibrium manifold is $\varepsilon = \{x \in R^4 | x_1 = \alpha \in R, x_2 = x_3 = x_4 \approx 0\}$. Apply the discrete-time feedback encoding of Figure 3c; reachability is preserved. Let $S$ be a change of coordinates such that $(S^{-1}AS, S^{-1}B)$ is in control canonical form. In the new coordinates, the equilibrium set is $\varepsilon = \{\beta 1_4, \beta \in R\}$. For corresponding equilibria in the two coordinate systems it holds $\alpha = S_F\beta$.

To obtain the required resolution of $\varepsilon$, choose a mesh size $\gamma = 2\varepsilon/(S_F)$ in $S$ coordinates. To this purpose, $W$ can be chosen to be any finite sets of integers, such that at least two of its elements are coprime, and inputs scaled as $u \in \gamma W$.

Figure 3 shows the symbolic control law design process. A PID controller is also designed for performance

**Figure 3** Symbolic control design process for aircraft control law

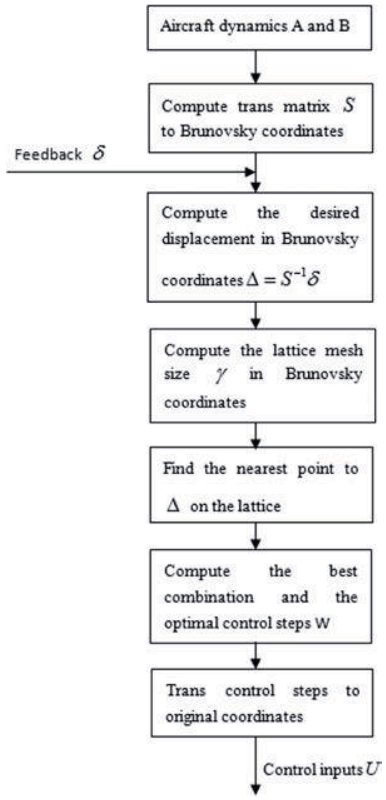



**Figure 4** Nested discrete-time continuous-time feedback encoding for aircraft control system

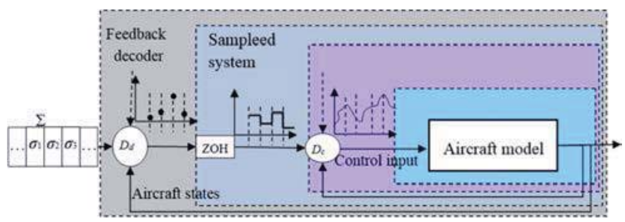
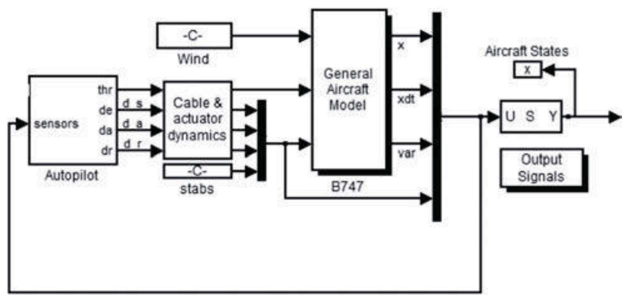



**Figure 5** System structure



comparison. Both the two controller are applied to nonlinear model. The control laws are evaluated for microburst encounters on the final approach. The aircraft tracks a reference descent rate using the altitude control law discussed in the preceding section. An aborted-landing maneuver is commanded using full throttle. The symbolic controller designed for aircraft control problem is based on nested discrete-time continuous-time feedback encoding, which is a kind of piecewise smooth encoding. The symbolic control structure for aircraft is shown in Figure 4. Figures 5 and 6 present the system structure and controllers in Simulink.

**Figure 6** Aircraft controller system block

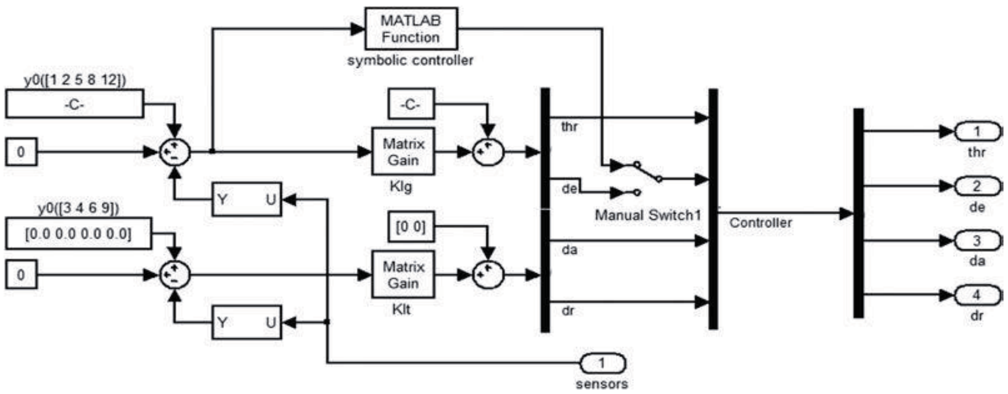
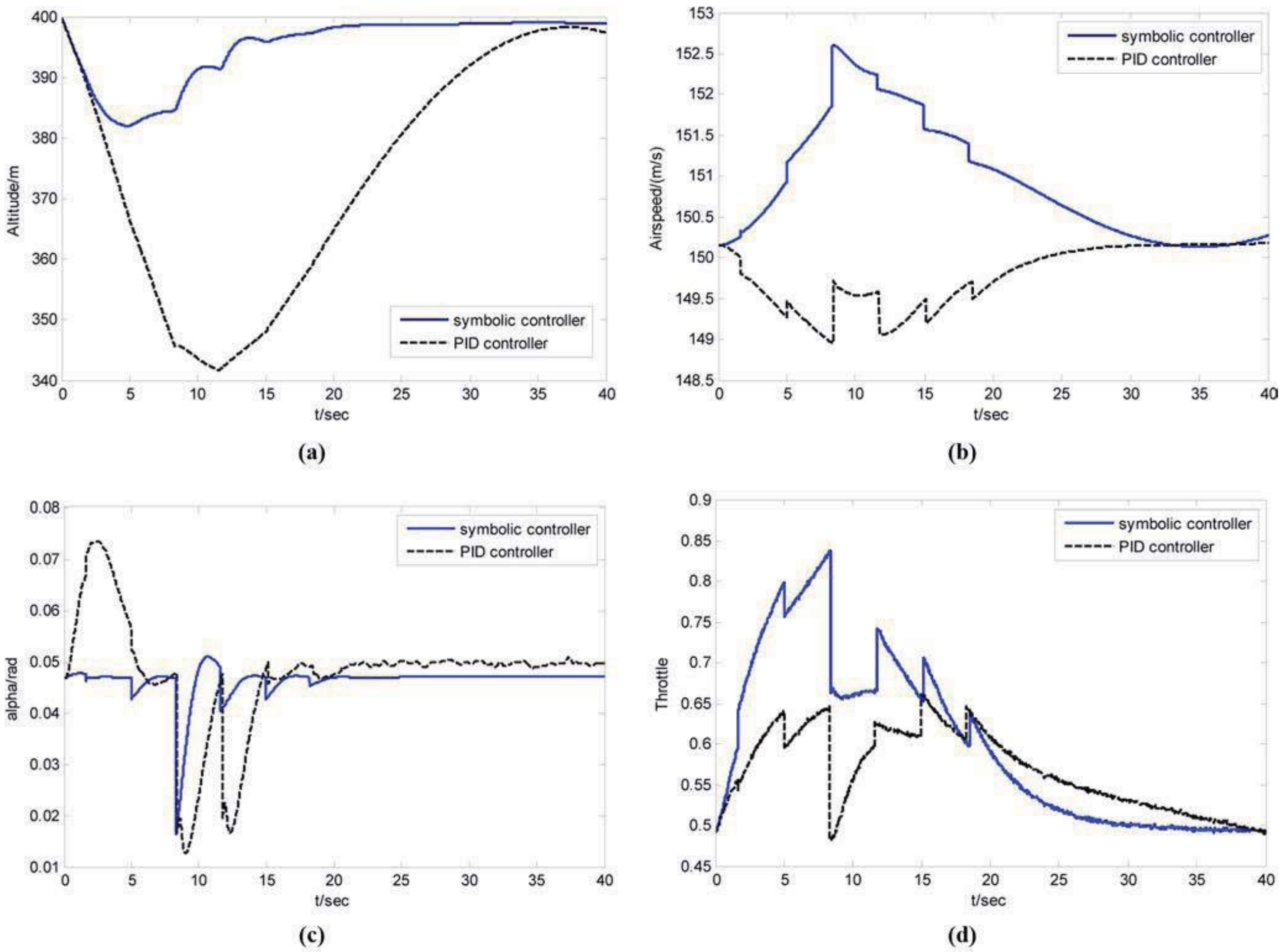



**Figure 7** The state and control histories obtained by symbolic controller and PID controller




**Notes:** (a) Altitude vs. time; (b) airspeed vs. time; (c) alpha vs. time; (d) throttle vs. time

## Simulation results

The dynamics A and B of B-747 is:

$$A = \begin{bmatrix} -0.0865 & -31.552-9.8 & 0 \\ 0 & 1.22830 & 0.9635 \\ 0 & 0 \; 0 & 1 \\ 0.0004 & -0.7343 \; 0 & -0.2918 \end{bmatrix}$$

$$B = \begin{bmatrix} -4.3271 & 0.2316 \\ -0.2191 & -0.0338 \\ 0 & 0 \\ -1.7591 & 0.0023 \end{bmatrix}$$

Considering the complexity of symbolic control inputs generating, we reduce the frequency of control factors for better control performance, although the sample frequency of aircrafts is much higher with unit sampling time T = 1s. Accordingly, the sampled system is:

$$x^+ = Ax + Bu = \begin{bmatrix} 0.91 & -52.08 & -9.38 & -24.11 \\ 0 & 2.67 & 0 & 1.50 \\ 0 & -0.50 & 0.99 & 0.72 \\ 0 & -1.15 & 0 & 0.30 \end{bmatrix} x + \begin{bmatrix} 14.29 & 15.32 \\ -1.53 & 0.84 \\ -0.70 & -1.34 \\ -1.17 & 0.21 \end{bmatrix} u$$

with scale factor $S_F = \|S1_4\| = 3.12$. The states $x$ are airspeed, angle of attack, pitch angle and pitch rate $[\Delta V \, \Delta\alpha \, \Delta\theta \, \Delta q]$ and the input $u$ are elevator $\delta_e$ and throttle $\delta_T$.

The problem for fixed integers $m > 0$, finding the best choice of an integer control set has been solved for $m = 2, 3, 4$, and the control input solving schemes would be more complicated with bigger $m$. Considering the complexity of numerous control inputs and the control performance, we use a rather small amount of control inputs with $m = 3$. Set $\varepsilon = 0.1$ and $\gamma = 0.057$. Then we get $N = 7$. We can observe that the plan takes $n = 6$ times $N$ sampling instants to complete execution, because of the dimension of the state-space.

The closest point on the reachable lattice is calculated as $\delta = (117\varepsilon, 0, 0, 0)$, according to a displacement of 60 m on the horizontal line. We can write $64\gamma l_4 = \gamma CU$, where $U = (0, 19, 23, 24)$ and $C$ is obtained by the min–max problem, here is:

$$\begin{bmatrix} 0 & -1 & 3 & 2 \\ 0 & -1 & 3 & 2 \\ 0 & -1 & 3 & 2 \\ 0 & -1 & 3 & 2 \end{bmatrix}.$$

Then we can get the string of control inputs and we choose $\overline{\ell T}$ as 1 s.

Figure 7 shows the state and control histories obtained using symbolic controller and PID controller. When the microburst comes, the altitude can be controlled back to 400 m in 20 s based on these two methods. Although aircraft states change rapidly in wind shear, the aircraft escapes wind shear field finally.

From the comparative simulation results, we can see that by using the control inputs generated by symbolic controller, the aircraft experienced less perturbation, which means more stability. The angle of attack response obtained by symbolic controller reaches to a maximum value (0.02 rad) at 7 s in Figure 7c, while the PID controller leads to worse performance. Related to the angle of attack response, by using the symbolic controller, the throttle increases quickly so the change of airspeed is quite small. The experimental results also show that the symbolic control law with climb rate scheduling can make effective control of aircraft performance to safely transit a very severe microburst.

## Conclusions

This paper presents a novel wind shear flight control law based on symbolic control. The simulation results suggest that with properly designed control laws, the aircraft considered in this study can safely transit a severe microburst. Satisfactory stability performance of the aircraft is showed in course of the flight. Symbolic control is an effective method for operational implementation, and the plane with symbolic controller has better stability in the wind shear. Considering the attitude and airspeed, symbolic controller can produce an actual increase of airspeed when encounter wind shear, which is more effective to get a recovery. An important issue of our future work will focus on how to enhance the automation level of our symbolic control approach for aircraft.

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