The Design and Implementation of Dive Maneuver

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Abstract. When it comes into air-to-air battlefield, using the dive maneuver, for an aircraft, has great realistically profound meaning in dominance of air domain and higher flexibility in attacking enemy planes below. Taking the task requirement and overload constraint into account, a mathematical model of dive maneuver is established and, further, the dynamic changing law of the fighter's parameters with smooth damp is designed. Simulation result shows that the model we used could shorten the time cost of dive maneuver compared to those of classic ones, leaving fighter more advantages in air combat.

Keywords: Dive maneuver · Overload constrain · Flight control

1 Introduction

1.1 A Subsection Sample

In aerial combat, the pilot steers the current position and posture of the aircraft through maneuver, so as to occupy the advantageous position in attack or avoid the attack from its opponent [1]. The victory in an air battlefield also depends on the maneuvering strategy of an airplane [2]. For example, an aircraft which has smaller mass and stronger maneuver could take advantage from its smaller turning radius to avoid attack or obtain favorable position; Through dive maneuver or strong thrust, an aircraft with bigger mass and faster speed could further improve its flight speed to get rid of the pursuit.

Dive maneuver is indispensable for modern fighters [1], since it plays a key role in the air battle and has a strong practical significance to compete for the airpower in the battlefield. On the one hand, missiles or bombs often use dive maneuver to attack at the end of flight, whose trajectory show as a sharp turn in the vertical plane at that time, and then they will accelerate in a straight line [3]. During that, the trajectory of dive maneuver directly determines the operational effectiveness of weapon system [4]; on the other hand, pilots change the current position and posture of the aircraft through dive maneuver, making it occupy a favorable position to attack or escape attack from its opponent.

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The realization of maneuver capable of altering height and direction of the airplane, such as dive maneuver and hover maneuver, mainly considers the trajectory traits of aircraft. Meanwhile, actually for better performance, it needs to consider the maneuver task requirements (such as desired height and expected speed) and the limitation of aircraft hardware and mechanical conditions (such as overload). Therefore, assuming the aircraft could meet instantaneous torque equilibrium condition, we use dynamics course equations presenting the motion of aircraft, at the mercy of overloads in 3-DOF. Then, in consideration of overload limitation and digital signal processing technology, the changing law of course elements with smooth damp (course roll, course yaw and course pitch etc.) are designed. In the end, those laws above are as the expected input of the flight control system to implement the dive maneuver.

1.2 Maneuver Model Establishing with Smooth Damp

The generation of maneuver focuses on the discussion of course characteristics in which overload constraints act as a primary factor. To this end, the navigation model of vehicle in three degrees is considered in geography coordinate system (x , y and z lies northward, upward and eastward, respectively).

$$\begin{cases} \dot{v} = g(n_x - \sin\theta) \\ \dot{\theta} = g(n_y \cos\gamma_s - \cos\theta)/v \\ \dot{\psi}_s = -g n_y \sin\gamma_s/(v\cos\theta) \\ \dot{x} = v\cos\theta\sin\psi_s \\ \dot{y} = v\sin\theta \\ \dot{z} = -v\cos\theta\sin\psi_s \end{cases} \quad (1)$$

where v is the velocity vector; g is gravity acceleration; n_x is the tangential overload; θ is the course pitch; n_y is the normal overload; γ_s is the course roll; ψ_s is the course yaw; x is the displacement northward; y is the displacement upward; z is the displacement eastward. It should be pointed out that the sideslip angle and the lateral force are assumed to be zero in (1). Generally, this assumption is reasonable, for lateral force do not need to be considered in the maneuver such as BTT (Bank to Turn), hovering and diving.

In order to generate the desired maneuver, the variation rules of the course elements $(\theta, \psi_s, \gamma_s)$ are given under the limitation of overload. The overload is calculated with the following equation

$$\begin{cases} n_x = \dot{v}/g + \sin\theta \\ n_y = (v\dot{\theta}/g + \cos\theta)/\cos\gamma_s \end{cases} \quad (2)$$

with

$$\begin{cases} n_x \leq n_{xm} \\ n_y \leq n_{ym} \end{cases} \tag{3}$$

In general, the overload limitation includes four aspects: the available thrust of engine, the available moment of rudder, the endurance of the aircraft structure and the physiological endurance of pilots.

Considering the principle that jerk (jerk is a physical term used to describe the changing rate of acceleration or force. The bigger the jerk, the more likely it renders material fatigue.) should not change in a rocket way, according to mechanics of materials, parameters with smooth damp are given directly by the model in order to reduce the difficulty of the design of the flight control system. In the process of modeling, thus, the design principle of flight control system is just to improve the tracking accuracy as much as possible, without considering additional damp characteristics. For this purpose, the following model constraints are applied

$$\frac{dn}{dt} < \infty (n = n_x, n_y) \tag{4}$$

Which means $|\dot{n}| < +\infty$; It will be no longer re-state in the latter section.

Thus, the problem of maneuver generation is converted into solving nonlinear functional problems satisfying certain requirements in a particular space. Specifically, below gives the mathematical model:

$$\theta^* = \theta(t); \psi_s^* = \psi_s(t); \gamma_s^* = \gamma_s(t) \tag{5}$$

$$s.t. \begin{cases} \theta^* \in C^2[D(\theta)] \\ \psi_s^* \in C^2[D(\psi_s)] \\ \gamma_s^* \in C^2[D(\gamma_s)] \\ (1) \sim (4) \end{cases} \tag{6}$$

Where $D(\theta)$ is the definition domain of θ, which is usually obtained by experience. For example, in dive maneuver the value of θ ranges within $[0, \pi/2)$. $C^2[\cdot]$ here is an operator representing all the functions with its second order derivative not only existential but consecutive on $D(\cdot)$.

1.3 Design of Maneuver

The dive maneuver could be divided into three stages: entry, straight flight and recovery [5–7], which are shown in Fig. 1.

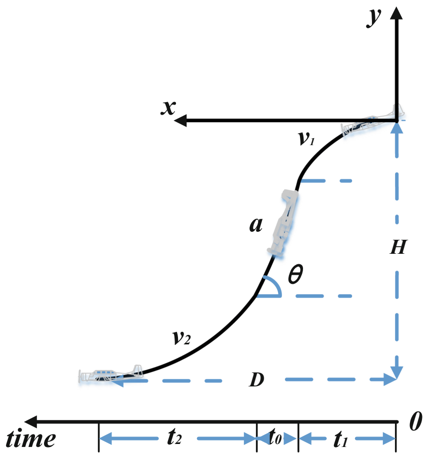

Fig. 1. Schematic diagram of dive maneuver.

where v_1, v_2 represents the velocity vectors at beginning of entry sand recovery respectively; a is the acceleration improving the velocity in straight state; t_1, t_0, t_2 is the time cost in the entry, the straight and the recovery, respectively; x is the displacement northward; y is the displacement upward.

Obviously, the expected values of the course yaw and the course roll should be zero in the whole process.

To analyze the varying traits of course element, we consider

$$\begin{cases} n_y = v\dot{\theta}/g + \cos\theta \\ \dot{n}_y = (v\ddot{\theta} + \dot{v}\dot{\theta})/g - \dot{\theta}\sin\theta \end{cases} \tag{7}$$

Clearly, in order to ensure boundedness of $\dot{n}_y$, neither $\dot{\theta}$ nor v can change suddenly.

To this end, the upcoming problem is that whether we could simplify the modeling process getting the anticipant course parameters in assumption of that the overload changes linearly.

Theorem 1. It is impossible to get the apt changing laws of course elements by randomly assigning a bounded known function to $\dot{n}_y$.

Proof: as Fig. 1 illustrates, the changing rule of θ is supposed to alter gradually from 0 to a negative number, and then back to zero, thus the statement above holds. ■

According to Theorem 1, in order to meet the overload limitations, the variation rule of the course pitch must be designed indirectly. To simplify the analysis, the following assumptions are established:

Hypothesis 1: during the dive maneuver, the velocity's magnitude during the entry phase and the recovery phase keep unchanged; in the straight flight stage, the velocity increases with an acceleration that would not change abruptly. Under the limitations above, define that the speed is maintained as at the beginning of the entry stage, say, v_1; likewise, it should be v_2 during the recovery phase; the maximum acceleration is a_m in the straight flight stage. At last, in order to simplify the analysis process, the course pitch is supposed to be zero before entry stage and after the recovery stage.

The speed changing process is dominated by n_x, according to (1). At this point, the problem (5) is simplified as

$$\theta^* = \theta(t) \tag{8}$$

As is stated above, $\ddot{\theta} < \infty$ is requested to satisfy $\dot{n}_y < \infty$, thus we can assume that alters in a most simple way, say a constant number or zero accordingly. More specifically,

$$\ddot{\theta} = \begin{cases} 2h_1/t_1 & 0 < t < t_1/2 \\ -2h_1/t_1 & t_1/2 < t < t_1 \\ 0 & t_1 < t < t_1 + t_0 \\ -2h_2/t_2 & t_1 + t_0 < t < t_1 + t_0 + t_2/2 \\ 2h_2/t_2 & t_1 + t_0 + t_2/2 < t < t_1 + t_0 + t_2 \end{cases} \tag{9}$$

where $h_i(i = 1, 2)$ is a constant. Then the change rate of course pitch is given by the following equation.

$$\dot{\theta} = \begin{cases} 2h_1 t/t_1 & 0 < t < t_1/2 \\ -2h_1 t/t_1 + 2h & t_1/2 < t < t_1 \\ 0 & t_1 < t < t_1 + t_0 \\ -2h_2 t/t_2 + 2h_2 \frac{t_0 + t_1}{t_2} & t_1 + t_0 < t < t_1 + t_0 + t_2/2 \\ 2h_2 t/t_2 - 2h_2 \frac{t_0 + t_1 + t_2}{t_2} & t_1 + t_0 + t_2/2 < t < t_1 + t_0 + t_2 \end{cases} \tag{10}$$

then we can get the course pitch:

$$\theta = \int_0^{t_0 + t_1 + t_2} \dot{\theta} dt \tag{11}$$

with the limitation of

$$0 < \theta < \max(\theta) =: \theta_E \tag{12}$$

where θ_E is dive angle, as defined in Fig. 1. The general variation rule of θ is shown as Fig. 2.

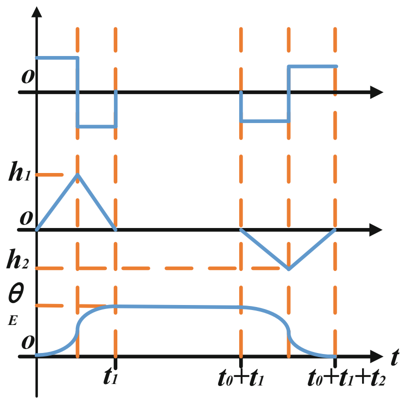

Fig. 2. Change law of course pitch and its first order and second-order differential.

Obviously

$$\begin{cases} \frac{h_1 t_1}{2} = \theta_E \\ \frac{h_2 t_2}{2} = \theta_E \end{cases} \tag{13}$$

From the limitations of overload that

$$\begin{cases} \frac{v_1 h_1}{g} + \cos\theta_1 \leq n_{ym} \\ \frac{v_2 h_2}{g} + \cos\theta_2 \leq n_{ym} \end{cases} \tag{14}$$

where $0 \leq \theta_1, \theta_2 \leq \theta_E < \pi$, and the condition that

$$\sup_{0 \leq \theta_i \leq \theta_E} \cos\theta_i = 1, (i = 1, 2) \tag{15}$$

we can get

$$v_i h_i \leq g(n_{ym} - 1) = const \quad i = 1, 2 \tag{16}$$

In order to reduce the time cost of maneuver, (16) can hold as equation, namely left equals to right. Thus, (16) is changed into

$$h_i = g(n_{ym} - 1)/v_i \tag{17}$$

thus

$$t_i = 2\theta_E/h_i \qquad i = 1, 2 \tag{18}$$

In the stage of straight flight, there exists

$$\begin{cases} n_x = a/g + \sin\theta_E \leq n_{xm} \\ a \leq g(n_{xm} - \sin\theta_E) \end{cases} \tag{19}$$

It can take its equality sign to reduce the motorized time. Therefore,

$$a_m = g(n_{xm} - \sin\theta_E) \tag{20}$$

Assuming $\dot{a}$ and $\dot{\theta}$ have the similar change law, we can obtain

$$v_2 = v_1 + S(a \sim t) = v_1 + a_m t_0/2 \tag{21}$$

where $S(a \sim t)$ represents the area between the curve and the t axis in the $acc - time$ figure. See Fig. 1 (21) can then be changed into

$$t_0 = \frac{2(v_2 - v_1)}{a_m} \tag{22}$$

Obviously, the time cost of maneuver depends on its specific purpose of how much the alteration of height and velocity should be. And there comes the following conclusions:

Theorem 2. Under the condition of smooth damp and the limitation of maximum available overload, the dive maneuver designed by the scheme (9)–(21) is optimal which consumes the least time in a sense, and has the best stationarity (smoothly maneuvering process).

Proof: it is obvious from the deduction. ■

With the expected variation of height and velocity,θ_E can then be designed.

At this point, it is necessary to consider whether any two of the expected velocity variation, the expected height variation and the expected northward variation can be quantitatively designed simultaneously during the dive maneuver.

Theorem 3. It is impossible to design the expected velocity variation, the expected height variation and the expected northward variation through scheme (9)–(21) at the same time. However, any two of the three expected can be optionally designed, and the one left would be uniquely determined by the formal two. That is to say, $\Delta v, \Delta X, \Delta H$ are not independent to each other.

Proof: the conclusion of Theorem 3 is obvious from the derivation process. ■

It means,

$$\Delta X = \Delta X(\Delta v, \Delta H) \tag{23}$$

Or

$$\Delta v = \Delta v(\Delta X, \Delta H) \tag{24}$$

$$\Delta H = \Delta H(\Delta X, \Delta v) \tag{25}$$

1.4 Simulation of Dive Maneuver

The parameter settings in the dive maneuver process are shown in Table 1.

Table 1. The parameter settings in the dive maneuver process.

Variable	Value	Variable	Value
v_1	200 m/s	v_2	300 m/s
θ_E	−60 deg	n_{xm}	6.0
n_{ym}	8.0	H_0	7000 m

where H_0 is the initial height of the aircraft in the beginning of the dive maneuver. Other parameters recorded during the dive maneuver process are shown in Table 2.

Table 2. Other parameters during the dive maneuver process.

Variable	Value	Variable	Value
t_0	3.9751 s	t_1	7.1238 s
t_2	10.6857 s	a_m	50.3130 m/s^2
ΔH	−3009.5 m	ΔX	4217.5 m

where ΔH is the decrement in height, ΔX is the progress made in the direction of x axis.

The variation curves of each course characteristic variables are shown in Fig. 3.

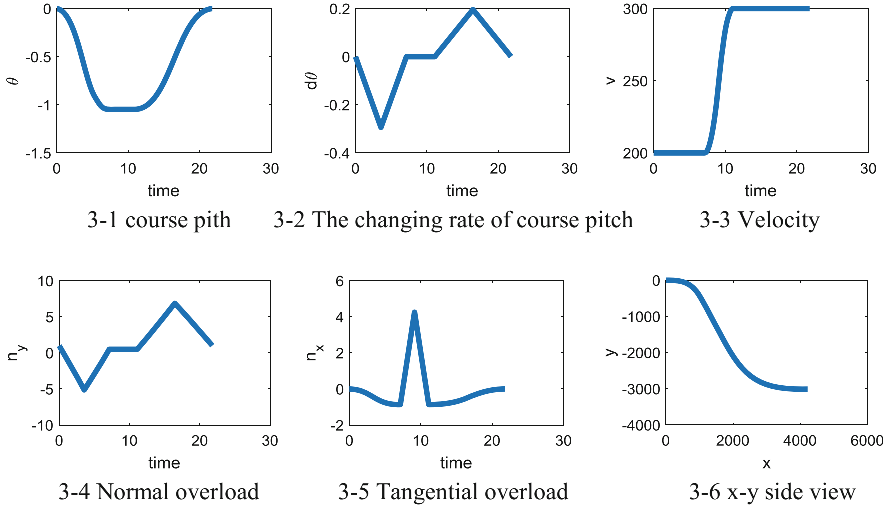

Fig. 3. The variation curves of each course characteristic variables

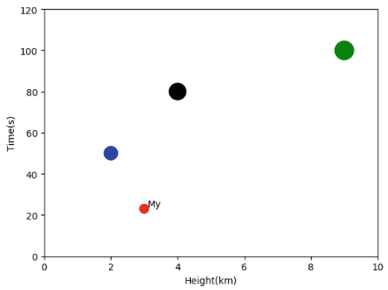

Fig. 4. Comparision results with other dive maneuver algorithms. The red circle is the algorithm result of this paper. The blue circle is the algorithm result of [8]. The black and green circles are the algorithm results of [9] (Color figure online).

Results shows aircraft consumes about 23 s when the height changes 3000 m. However, in [8], the scheme designed for dive maneuver used about 50 s when the height changes 2000 m. The results validate the effectiveness of Theorem 2 from another picture; in [9], the height change with 9000 m uses about 100 s, with 4000 m takes about 80 s (Fig. 4).

1.5 Conclusion

Dive is the process of converting the gravitational potential energy into kinetic energy. Fighter attacks enemy planes below through changing the height difference between itself and the enemy. In the article, the mathematical model of dive maneuver is established and, further, the dynamic changing law of the fighter's parameters with smooth damp is designed. After that, the simulation is carried out according to the UAV data in the air combat process. Comparing the simulation results with other related paper, we find that the time cost is shorter than the classic ones. Besides, the comparison also proves the rationality and effectiveness of this model.

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