Study on Multi-parameter Coupling Mechanism of a Dual-channel Controlled Ejection Seat

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ABSTRACT

Aiming at research on the coupled control of ejection seat attitude rocket under unfavorable attitude, we provide multi-parameter coupling mechanism of a dual-channel controlled ejection seat. We use a dual-channel (roll, pitch) controlled ejection seat as the research object. On the basis of deriving the mathematical model of its ejection motion, combining with the working principle of the ejection seat, and according to the preliminary drafted various control modes, together with both qualitative analysis numerical simulation methods, the multi-parameter coupling mechanism of the seat with specific roll and pitch ejection states is studied, and the research shows the dual-channel controlled has a beneficial effect on the trajectory of the ejection process.

Keywords: Ejection seat, Dual-channel control, Multi-parameter coupling, Attitude rocket

1. INTRODUCTION

One of the important trends in the development of ejection seats is intelligentization[1,2]. That is, according to the different ejection conditions, the changes of its attitude and motion trajectory are adaptively controlled[3], in order to reduce least altitude required for safe ejection as much as possible[4]. How to design and iterate better control strategies is the basis for the development of a new generation ejection seats. The design of ejection seat control strategy must be guided by simulation. Through regression analysis of a large amount of simulation data, a suitable control strategy is determined and optimized iteratively[5,6]. During the simulation of ejection seat movement, multiple state parameters (such as flight speed, aircraft sinking rate, aircraft dive angle, aircraft roll angle, etc.) and controllable parameters (such as attitude control force and its working time, main power force and its working time, parachute control time, etc.)are included, there is a coupling relationship between these parameters[7,8]. The coupling relationship must be studied first before the control strategy design can be done based on numerical simulation. In this article, the dual-channel (roll, pitch) control ejection seat is the research object, and its multi-parameter coupling mechanism is studied.

The main research contents of this article are: a) Derive the mathematical model of the seat ejection movement; b) Draft the initial control mode of the attitude rocket; c) Qualitatively analyze the influence of attitude rocket on seat motiontrajectory and attitude; d) Simulate and analyze the changes of seat movement trajectory and attitude under various control modes; e) Draw conclusions on the analysis of the multi-parameter coupling mechanism according to simulation results.

2. BASIC RESEARCH

Aiming at research on the coupled control of ejection seat attitude rocket under unfavorable attitude, we use the method which combines both theoretical analysis and numerical simulation. First, carry out a qualitative analysis based on the mathematical model of the ejection, and determine possible ejection seat's trajectory and attitude changes under different control modes of the attitude rocket. Then write a simulation program based on the mathematical model and parameters of certain ejection seat, run the program and verify the theoretical analysis results[9,10]. In order to study the coupled control of the roll and pitch attitude rockets in unfavorable attitudes, and to make the analysis representative, we select the state with both the dive angle and the roll angle for numerical simulation.

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2.1 A brief derivation of the mathematical model of seat ejection

Based on the mathematical model of an advanced ejection seat, the moment of force from the attitude rocket is added in the freefly phase. The impulse of the roll attitude rocket is set to 300$N{\cdot}s$, and the pitch attitude rocket's impulse is set to 450$N{\cdot}s$. The time of effect is 80ms. We assume that the attitude rocket only affects the moment when it is working, ignoring the influence of attitude rocket, and briefly derive the mathematical model of seat ejection movementduring freefly phase. The torque received by the seat during freefly is:

$$M_s = M_{aero} + M_{roc} + M_{att} \tag{1}$$

In equation(1), M_{aero} is the aerodynamic moment on the seat, M_{roc} is the dynamic moment produced by the main rocket, its magnitude is related to the eccentricity of the main rocket thrust line, and M_{att} is the control moment produced by the attitude rocket. Equation(1) is based on body axis coordinate system of the human-chair system. In this coordinate system, the momentum moment of the human-chair system is:

$$\begin{bmatrix} h_x \\ h_y \\ h_z \end{bmatrix} = \begin{bmatrix} w_x I_x - w_y I_{xy} - w_z I_{xz} \\ -w_x I_{xy} + w_y I_y - w_z I_{yz} \\ -w_x I_{xz} + w_y I_{yz} + w_z I_z \end{bmatrix} \tag{2}$$

According to the theorem of moment of momentum, write the rotation dynamics equation of the human-chair system and expand it, and equation(3) can be obtained.

$$\begin{bmatrix} \frac{dh_x}{dt} + (h_z w_y - h_y w_z) \\ \frac{dh_y}{dt} + (h_x w_z - h_z w_x) \\ \frac{dh_z}{dt} + (h_y w_x - h_x w_y) \end{bmatrix} = \begin{bmatrix} M_{s,x} \\ M_{s,y} \\ M_{s,z} \end{bmatrix} \tag{3}$$

Assuming that the person-chair system is symmetric with respect to (certain plane), therefore:

$$I_{xy} = I_{yz} = 0 \tag{4}$$

Expand and simplify the equation(3),and equation(5) can be obtained:

$$\begin{bmatrix} I_x \frac{dw_x}{dt} - I_{xy} \frac{dw_y}{dt} \\ I_y \frac{dw_y}{dt} - I_{xy} \frac{dw_x}{dt} \\ I_z \frac{dw_z}{dt} \end{bmatrix} = \begin{bmatrix} M_{s,x} \\ M_{s,y} \\ M_{s,z} \end{bmatrix} + \begin{bmatrix} (I_y - I_z) w_y w_z - I_{xy} w_x w_z \\ (I_z - I_x) w_x w_z + I_{xy} w_y w_z \\ I_{xy}(w_x^2 - w_y^2) - (I_x - I_z) w_x w_y \end{bmatrix} \tag{5}$$

According to the above model, the moment and angular velocity can be solved iteratively, and then the Euler angle can be solved by the quaternion method[11]. The quaternion method is more commonly used, and it is not the main content discussed in this article, so we will not introduce it in detail here.

2.2 Preliminary control mode of the attitude rocket

Since the research object of this article is a dual-channel controlled ejection seat, the typical working conditionis with some dive angle and roll angle. Set the aircraft speed Vc equal 450km/h at the moment of ejection, the dive angle equal 45°, and the roll angle equal 45°. Under this specific initial condition, and for the purpose of studying coupled control mechanism of the roll and pitch attitude rockets in unfavorable attitudes, the following 10 attitude rocket control modes are preliminarily formulated for simulation analysis, as the basis for subsequent in-depth research. a) Control mode 1: After ejection from the cockpit, the roll attitude rocket and the pitch attitude rocket will notwork, and the main rocket will work immediately; b) Control mode 2: After ejection from the cockpit, the roll attitude rocket works,and the main rocketwill work after a delay of 80ms, and the pitch attitude rocket will not work; c) Control mode 3: After ejection from the cockpit, the pitch attitude rocket works, and the main rocket will work after a delay of 80ms, and the roll attitude rocket will not work; d) Control mode 4: After ejection from the cockpit, the roll attitude rocket and the pitch attitude rocket work at the same time, and the main rocket works after a delay of 80ms; e) Control mode 5: After ejection from the cockpit, the roll attitude rocket works first, and the pitch attitude rocket will work after a delay of 80ms, and the main rocket will work after the attitude rocket work completed; f) Control mode 6: After ejection from the cockpit, the roll attitude rocket works first, and the pitch attitude rocket will work after a delay of 100ms, and the main rocket will work after the attitude rocket work completed; g) Control mode 7: After ejection from the cockpit, the roll attitude rocket works first, and the rocket will work in the pitch attitude after a delay of 200ms, and the main rocket will work after the attitude rocket work completed; h) Control mode 8: After ejection from the cockpit, the pitch attitude rocket works first, after a delay of 80ms, the roll attitude rocket will work, and the main rocket will work after the attitude rocket work completed; i) Control mode 9: After ejection from the cockpit, the pitch attitude rocket works first, after a delay of 100ms, the roll attitude rocket will work, and the main rocket will work after the attitude rocket work completed; j) Control mode 10: After ejection from the cockpit, the pitch attitude rocket works first, after a delay of 200ms, the roll attitude rocket will work, and the main rocket will work after the attitude rocket work completed.

3. QUALITATIVE ANALYSIS OF THE INFLUENCE OF ATTITUDE ROCKET

3.1 Analysis of the influence of attitude rocket on ejection trajectory

Under the conditions of 45° dive angle and 45°roll angle, the influence of the attitude rocket on the ejection trajectory mainly has following two aspects: a) Due to the existence of a large dive angle, the trajectory altitude loss will not be prevented during the operation of the attitude rocket. When the dive angle of the aircraft is of a large positive value, there will be a downward velocity after the seat is ejected out of the cockpit. This velocity component has positive correlation to the aircraft's airspeed and dive angle. Therefore, when the airspeed of the aircraft is 450km/h and the dive angle of 45° and the roll angle of 45° exist, the downward velocity component of the seat after ejecting out of the cockpit is relatively large. At this moment, if the attitude rocket works first, and then the main rocket works again, the seat will continue to fall during the attitude rocket working period, which will adversely affect the trajectory altitude of the ejection process. b) Attitude rocket could in some way correct the seat’s attitude, making the main rocket work more effective and generating upward thrust. When the roll angle and pitch angle are large, and the attitude rocket is not used for correction, the thrust of the main rocket does not necessarily push the seat up, and may even completely push seat to other directions. Taking the working conditions considered in this article as an example, if the attitude rocket does not work, the main rocket will generate thrust to upper left or right, which can reduce the falling speed to certain extent, but the effect is not obvious. Under this working condition, if the attitude rocket is working, you can first adjust the seat into a proper attitude, and then push the seat up by the main rocket, so that most of the impulse generated by the main rocket is used to reduce the seat from falling, which has a beneficial effect on the trajectory of the ejection process[12,13].

3.2 Analysis of the influence of attitude rocket on seat attitude

The purpose of installing an attitude rocket on the ejection seat is to make the seat correct back to the normal attitude as soon as possible after being ejected out of the cockpit, that is, the roll angle approaches 0° and the pitch angle has a small positive value. Theoretically speaking, as long as the attitude rocket works, the ejection seat attitude can be improved by its moment of force, but the attitude rocket will produce a relatively large angular velocity during the process of adjusting seat’s attitude. Taking the roll attitude rocket as an example, the roll attitude rocket on one side will produce a large roll angular velocity acceleration after working, and the roll attitude rocket on the other side is required to generate the opposite roll moment of force to prevent and reduce the roll angular velocity acceleration.

If the roll attitude rocket and the pitch attitude rocket are set to work at the same time, a larger yaw rate may occur after the attitude rocket works. The reason for producing the angular velocity will be explained through the following analysis of the mathematical model.

Because body axis coordinate system of the human-chair system is a inertial coordinate system which is rotating the angular acceleration of rotation is not only related to the moment of force, but also related to the moment of inertia, the product of inertia and the angular velocity. It can be shown in the last term of the following (See equation (5)) .

When the attitude rocket is not working, the roll angular velocity ω_x and the yaw angular velocity ω_y are usually very small. Due to the existence of the eccentricity, certain pitch angular velocity ω_z will appear. According to the analysis of equation (5), it is found that the value of the last term is relatively small and will not have significant impact on the rotation of seat.

When the roll attitude rocket or the the pitch attitude rocket works alone, it will produce a larger roll angular velocity ω_x or pitch angular velocity ω_z during its working time. A larger roll angular velocity will have impact on the pitch direction and the yaw direction, among which the influence on the yaw direction is greater, and the influence on the pitch direction is smaller. The pitch angular velocity ω_z has few effect on the roll and yaw directions.

When the roll attitude rocket and the pitch attitude rocket work sequentially, the coupling effect of roll and pitch is still not obvious. Under normal circumstances, when the two attitude rockets work, there will not be a large roll angular velocity, and there may be some pitch angular velocity, but it should still be within a controllable range.

When the roll attitude rocket and the pitch attitude rocket work at the same time, the roll angular velocity ω_x and the pitch angular velocity ω_z are both large. At this moment, the control effects of the two attitude rockets are coupled, that is, the roll control and the pitch control affect each other. This effect will produce moments in both roll direction and pitch direction, making the attitude of the ejection seat no longer controlled as expected. The most significant impact is that when the roll attitude rocket and the pitch attitude rocket finish working, there will still be a large roll angular velocity and a pitch angular velocity, as well as a yaw angular velocity. The existence of these angular velocities will affect the straightening and full expansion of ejection seat, and there may be phenomena such as parachute rope entanglement[14,15].

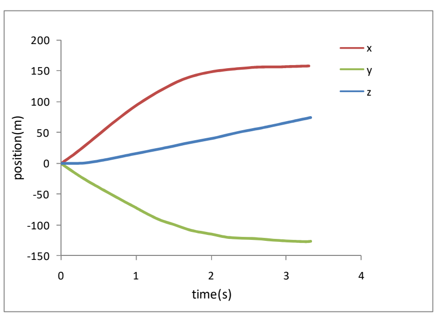
In summary, the influence of all circumstances, such as both attitude rockets fail to work, one of the attitude rockets working alone or the attitude rockets work one after the other, are all controllable. Seat's attitudecan be corrected under all these circumstances, and great angular velocities in three directions will not appear. However, if the roll and pitch attitude rockets work at the same time under the coupled control of the roll attitude rocket and the pitch attitude rocket, angular velocities in three directions will be generated after the attitude rocket work ends, and an uncontrollable attitude will occur. This is unfavorable for safe ejection of the seat.

4. SIMULATION AND ANALYSIS OF SEAT MOTION UNDER VARIOUS CONTROL MODES

The simulation parameters are set as follows: aircraft airspeed V_c equal 450km/h, dive angle equal 45°, roll angle equal 45°, and angular velocities on all direction are zero. Based on the 10 proposed attitude rocket control modes, we takes the first, third, fifth, seventh, and ninth control modes as examples to list the simulation results and perform necessary analysis.

4.1 Simulation analysis of control mode 1

Control mode 1 is that after exiting the cockpit, the roll attitude rocket and the pitch attitude rocket will not work, and the main rocket will work immediately. In this control mode, the seat motion trajectory and attitude angle curve in the freefly stage are shown in Figure 1.



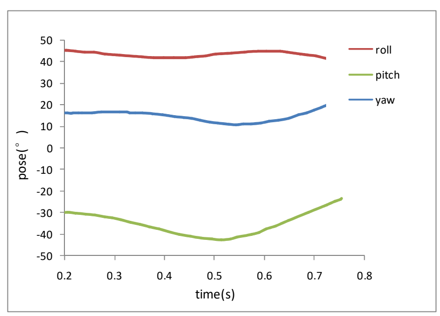


Figure 1. The trajectory and attitude change curve corresponding to control mode 1.

Analysis: When the attitude rocket is not working, the roll moment and the yaw moment are both small, and only certain pitch moment is generated due to the eccentricity of the main rocket. Therefore, the roll angular velocity is also small, and the roll angle is stable at 40°～45°. In this case, the full parachute can be reached relatively quickly, and the final trajectory altitude is relatively normal.

4.2 Simulation analysis of control mode 3

Control mode 3 is that after exiting the cockpit, the pitch attitude rocket works, and the main rocket will work after a delay of 80ms, and the roll attitude rocket will not work. In this control mode, the seat attitude angle and motion trajectory curve in the freefly stage are shown in Figure 2.

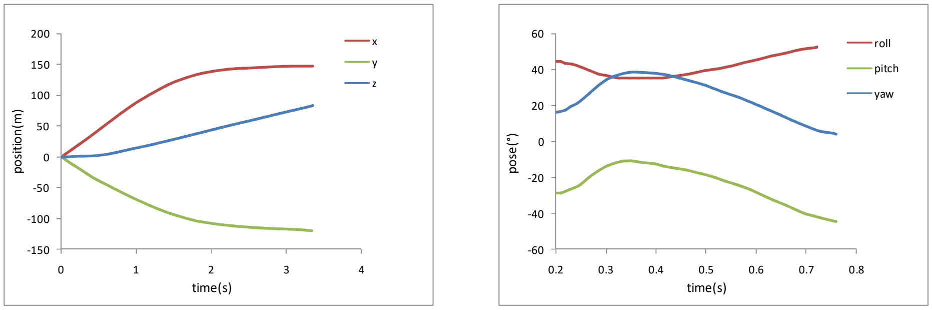


Figure 2. The trajectory and attitude change curve corresponding to control mode 3.

Analysis: When only pitch attitude rocket works and roll attitude rocket doesn't, the dive angle can be corrected quickly after seat exiting the cockpit, so that the main rocket thrust pushes the seat upward. In addition, the pitch attitude rocket basically does not affect the roll and yaw motion, which is consistent with the previous qualitative analysis.

4.3 Simulation analysis of control mode 5

Control mode 5 is that after exiting the cockpit, the roll attitude rocket works first, and the pitch attitude rocket will work after a delay of 80ms, and the main rocket will work after the attitude rocket work completes. In this control mode, the seat attitude angle and motion trajectory curve in the freefly stage are shown in Figure 3.

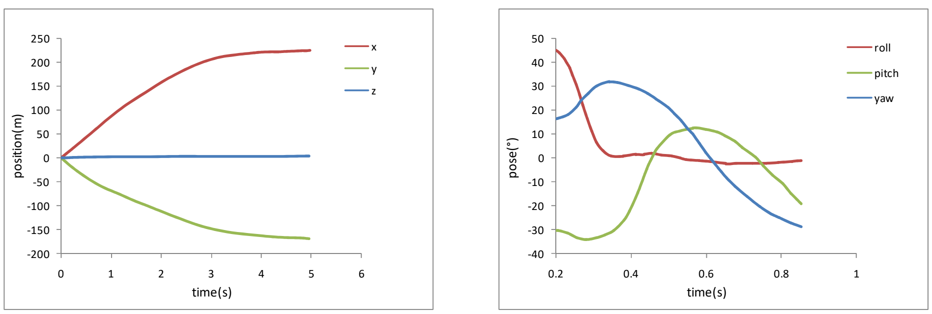


Figure 3. The trajectory and attitude change curve corresponding to control mode 5.

Analysis: After exiting the cockpit, the roll attitude rocket works first, and then the pitch attitude rocket works, which can better correct the roll and pitch angles. However, the trajectory altitude is lost while correcting the attitude, which makes the trajectory result obtained by simulation not very ideal. In addition, this control mode also brings a relatively large yaw rate.

4.4 Simulation analysis of control mode 7

Control mode 7 is that after exiting the cockpit, the roll attitude rocket works first, and the pitch attituderocket will work after a delay of 200ms, and the main rocket will work after the attitude rocket's work completes. In this control mode, the seat attitude angle and motion trajectory curve in the freefly stage are shown in Figure 4.

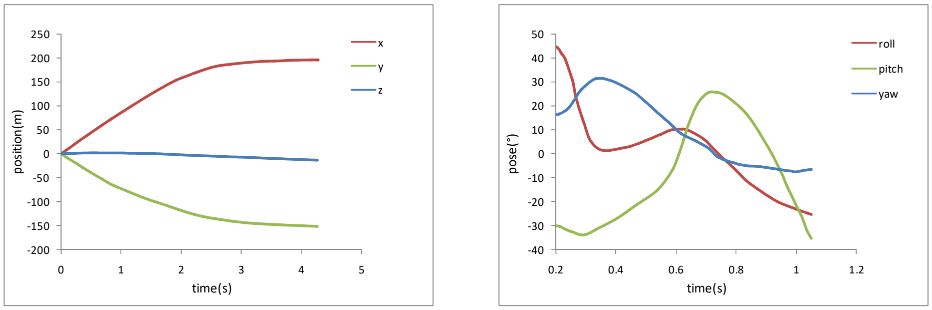


Figure 4. The trajectory and attitude change curve corresponding to control mode 7.

Analysis: Compared with the final trajectory altitude without delay of 200ms in the pitch attitude rocket, the trajectory altitude decrease compared to when it is with the delay of 100ms.

4.5 Simulation analysis of control mode 9

Control mode 9 is that after exiting the cockpit, the pitch attitude rocket works first, after a delay of 100ms, the roll attitude rocket will work, and the main rocket will work after the attitude rocket work completes. In this control mode, the seat attitude angle and motion trajectory curve in the freefly stage are shown in Figure 5.

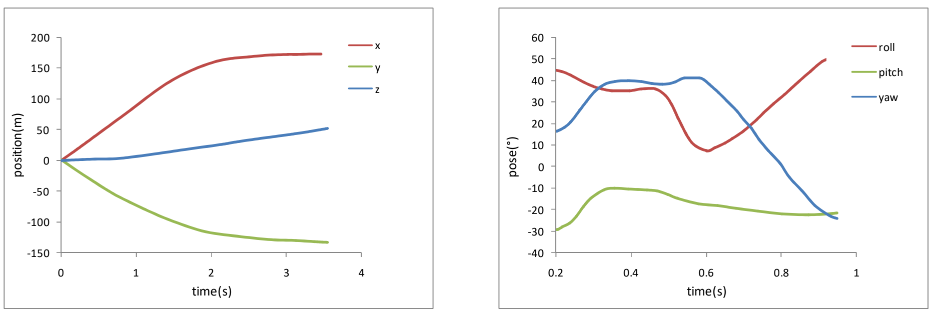


Figure 5. The trajectory and attitude change curve corresponding to control mode 9.

Analysis: Compared with the control mode without delay, the delay of the roll attitude rocket does not bring a beneficial effect, on the contrary, the trajectory altitude is reduced due to the delay.

4.6 Comparative analysis of seat motion trajectory altitude under various control modes

To evaluate the comprehensive performance of the ejection seat under various control modes, the most important thing is to analyze the altitude of its motion trajectory. In the actual working process, simulation has been carried out on all 10 control modes, and the obtained trajectory altitudes are shown in Table 1.

Table 1. Comparison table of trajectory altitudes obtained by different control modes.

Control mode	Trajectory altitude(m)	Control mode	Trajectory altitude(m)
1	-125.4	6	-144.6
2	-151.5	7	-152.1
3	-120.1	8	-124.3
4	-110.1	9	-134.6
5	-168.7	10	-149.1

Comparing the trajectory altitude shown in Table 1, it can be seen that the control mode 1, 3, 4, and 8 are better. Among them, the control mode 4 obtains the highest trajectory altitude, but the simultaneous control of the pitch attitude rocket and the roll attitude rocket will produce additional angular momentum, which is unfavorable for life-saving parachutes' working. Therefore, when a large dive angle and a large roll angle coexist, it is better to adjust the pitch angle first or only adjust the pitch angle. If dive angle is even larger, it is better to let the attitude rockets not workand launch the parachute as soon as possible. In the followresearch, the control mode will be subdivided according to the results of the multi-parameter coupling mechanism analysis to determine the specific and practical control mode.

5. CONCLUSIONS AND PROSPECTS

Through the above qualitative analysis and simulation result analysis, the following conclusions and prospects can be drawn:

a) In the situation of a large dive angle, we should weigh advantages of the attitude rocket against its disadvantages to determine whether the attitude rocket should start to work. Under the conditions of 45° dive angle and 45° roll angle, using the attitude rocket to correct the attitude can obtain a higher trajectory altitude;

b) The attitude rocket alone will not produce additional angular velocity after its work ends. The attitude rocket will produce determined additional angular velocity after its work is completed. At the same time, the attitude rocket will produce a larger additional roll angular velocity and yaw angular velocity, which will affect the straightening and full expansion of the parachute.

c) This article uses 45° dive angle and 45° roll angle as special cases to analyze the multi-parameter coupling mechanism. Although the case is representative, it is still necessary to perform similar analysis on more states of the ejection state spacein the actual work process, and get the corresponding analysis results.

APPENDIX

Funding acquisition, Jin Liying; Software, Wu Yibin; Validation, Wu Ming.

DATA AVAILABILITY STATEMENT

The data used to support the findings of this study were supplied by corresponding author under license and so cannot be made freely available. Requests for access to these data should be made to corresponding author.

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