

# Design of Control Law for Ejection Seat under Adverse Attitudes

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**Abstract.** The escape performance of ejection seat under adverse attitudes is the key technology for the 4th generation ejection seat, and the design of control law algorithm is the core problem for attitude and trajectory adjustment. A new control law design method was presented. Firstly, a simulation model for the entire ejecting process was established and a control parameter optimization model was designed, through which an optimum parameter set was obtained as the discrete control law. Then, by utilizing multilayer feedback of the error back propagation (BP) algorithm based neural network model, the ultimate continuous control law can be acquired under the whole ejecting conditions. The roll attitude ejecting condition was exemplified to design and validate the approached method. The results indicate that the performance of ejection seat by adopting the control law designed by the proposed method is higher than the multi-mode control law and the K36JI-3.5 ejection.

## 1 Introduction

The ejection seat is an important life-saving equipment for emergency escape and safe rescue of the pilot. After the ejection seat leaves the aircraft, the process needs to be controlled accordingly. When the seat has attitude trajectory control or high-speed airflow protection device, it is also necessary to determine the appropriate working parameters according to the specific ejection state. In summary, all controls involved in the timing or process of ejection seat operation are called the sequence control technology of the ejection seat.

Dual-mode sequence control can effectively reduce the delay time of parachute deploy in the case of medium and low-speed ejection, thus improving the performance of low altitude life-saving. And when the ejection height is high, increase an additional parachute delay time through the height threshold to enable the pilot to leave the adverse environment such as low temperature and hypoxia at high altitude as soon as possible, to avoid physical damage caused by adverse factors at high altitude. The US Air Force ACES- II ejection seat and the Russian K36 series ejection seat are using dual-mode sequence control technology [1-3]. In order to shorten the opening time of medium and low altitude ejection, Martin Baker Company further subdivides the low-altitude deceleration mode of the parachute opening time into 254 kinds in the MK16A seat 's sequence controller, to open the survival parachute as soon as possible [4]. Although this method solves the problem temporarily, it also exposes the fatal defect of the sequence control Law design with the modal classification as the basic principle. That is, as the state parameters increase, the mode division in the multidimensional space becomes

extremely complicated, and the critical values of the parameters are also difficult to be determined. In addition, each operating mode uses a single control parameter, so it is also difficult to guarantee the optimality of the control law. In this paper, a design method based on optimization theory model and neural network model is presented.

## 2 Design program

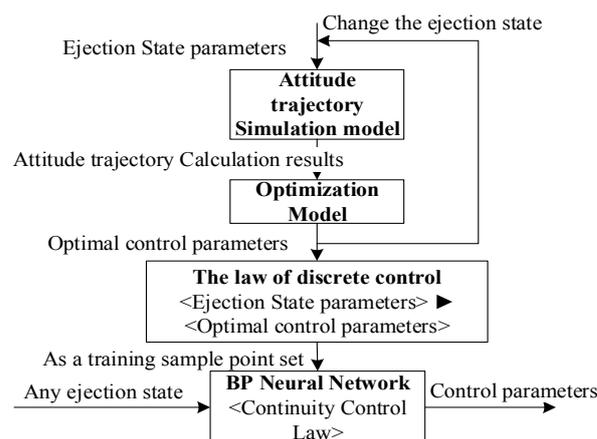


Figure 1. Design program for control law.

The control rule design flow proposed in this paper is shown in Fig.1. Through the simulation calculation program and the optimization model of the ejection seat attitude trajectory, it is inevitable to find the optimal control parameter value corresponding to a certain fixed ejection state, so that the ejection seat can meet the optimal lifesaving performance index. The discrete control law point set containing enough sample point data

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can be obtained by repeating the above optimization process in the global range of ejection state parameters. By using the point set as the sample data, designing the neural network model and training, the continuous nonlinear mapping process of the control law algorithm can be completed. The numerical model of neural network after convergence training is the final control law algorithm.

### 3 Ejection attitude trajectory calculation

#### 3.1 Mathematical model

In the simulation study of ejection, the constraints and forces are different at each stage, the corresponding dynamic models need to be established separately. Specific coordinate system definitions and mathematical models can be found in the literature [5-8]. Since the adjustment control of the ejection attitude trajectory in the adverse attitudes mainly acts on the free flight phase of the seat in the air, only the six degree-of-freedom dynamic equation of the human chair system in the body axis coordinate system is listed, such as the formula (1) as shown below.

$$\begin{bmatrix} \frac{dV_{xb}}{dt} \\ \frac{dV_{yb}}{dt} \\ \frac{dV_{zb}}{dt} \end{bmatrix} = \begin{bmatrix} \omega_{zb}V_{yb} - \omega_{yb}V_{zb} \\ \omega_{xb}V_{zb} - \omega_{zb}V_{xb} \\ \omega_{yb}V_{xb} - \omega_{xb}V_{yb} \end{bmatrix} + \frac{1}{m} \begin{bmatrix} F_{s,xb} \\ F_{s,yb} \\ F_{s,zb} \end{bmatrix} \quad (1)$$

$$\begin{bmatrix} I_x \frac{d\omega_{xb}}{dt} - I_{zx} \frac{d\omega_{zb}}{dt} \\ I_y \frac{d\omega_{yb}}{dt} \\ I_z \frac{d\omega_{zb}}{dt} - I_{zx} \frac{d\omega_{xb}}{dt} \end{bmatrix} = \begin{bmatrix} (I_z - I_y)\omega_{yb}\omega_{zb} - I_{zx}\omega_{xb}\omega_{yb} \\ (I_x - I_z)\omega_{zb}\omega_{xb} + I_{zx}(\omega_{xb}^2 - \omega_{zb}^2) \\ (I_y - I_x)\omega_{xb}\omega_{yb} + I_{zx}\omega_{yb}\omega_{zb} \end{bmatrix} + \begin{bmatrix} M_{s,xb} \\ M_{s,yb} \\ M_{s,zb} \end{bmatrix}$$

Where:  $[V_{xb}, V_{yb}, V_{zb}]$  is the component of the speed of the human-chair system in the body coordinate system.  $[\omega_{xb}, \omega_{yb}, \omega_{zb}]$  is the component of the rotational angular velocity of the human-chair system.  $m$  is the mass of the chair system.  $[F_{s,xb}, F_{s,yb}, F_{s,zb}]$  and  $[M_{s,xb}, M_{s,yb}, M_{s,zb}]$  are the components of the resultant force and resultant moment respectively.  $I_x, I_y,$  and  $I_z$  are moments of inertia of area.  $I_{zx}$  is the product of inertial, and  $I_{xy} = I_{yz} = 0$  based on the assumption that the human-chair system has a longitudinal symmetry plane.

Taking MSC.EASY5 as the basic platform, establish a universal ejection seat model library according to the function and structure characteristics of the ejection seat. Based on the characteristics of motion and mathematical model of each stage, a numerical simulation model of specific stage is constructed. Design the normative external data interface to facilitate the input and output of the data.

#### 3.2 Simulation model

Using MSC.EASY5 simulation software as the basic platform, according to the function and structure characteristics of the ejection seat, to establish a universal

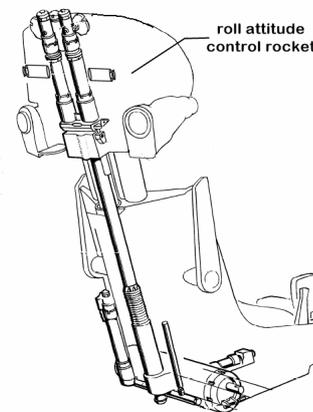
ejection seat model library. Based on the characteristics of motion and mathematical model of each stage, a numerical simulation model of specific stage is constructed. Design the normative external data interface to facilitate the input and output of the data. Because the optimization process in fixed ejection state needs to calculate different control parameters, and the complete control law needs to be repeatedly calculated in the global range of ejection state. This paper using batch commands to completes the automation of the calculation.

### 4 Control law design

#### 4.1 Control method

When the aircraft is in a low-altitude roll attitude for ejection, the life-saving capability of the ejection seat will be seriously reduced. Therefore, it is especially important to correct the roll attitude of the ejection seat. This paper takes the only roll adverse attitudes control as an example to carry out the design verification of the control law design method.

The control method includes two aspects. (1) Add a pair of roll attitude adjusting rockets at the back of the headrest parachute box, to correct the roll attitude by roll moment. (2) Add the main rocket switch, when the roll attitude adjusting rockets cannot produce effective correction, shut down the main rocket pack to avoid the loss of life-saving height caused by the main rocket.



**Figure 2.** Installation of roll adjusting rockets.

The parameters are the ignition time interval of the left and right roll rocket and the main rocket switch. It can be seen from the analysis that the former mainly problem is the optimal value in different ejection states, while the latter is the determination of the critical parameter value, which is the main limitation of the design method of the mode division control law.

#### 4.2 Optimized calculation model

According to the design program of control law of Fig.1, it is necessary to determine the optimal control parameter value by optimizing the calculation model for each fixed ejection state. For this optimization problem, the decision variable are the control parameters. Only consider to take

value range of decision variables as the constraint. Considering the control accuracy of the practical application of engineering, the accuracy of the delay ignition interval of the roll attitude rocket is defined as 0.1s, and must be less than the parachute opening time. No less than the parachute opening time means that the single-sided rocket does not have a practical effect. The value of the main rocket switch is defined as 0 or 1, in which 0 means shut down, 1 means normal operation. For the setting of the objective function, because it does not change the parachute opening time, it is considered that the dynamic load of opening parachute still satisfies the basic requirements of human physiological tolerance. Based on the minimum safe life-saving height, and the objective function and optimization target defined as the peak of trajectory height when the parachute fully opened, we can consider that the ejection seat has the best life-saving performance. In summary, the mathematical description of the final optimization problem is shown in Eq. (2).

$$\begin{cases} \max f_h(t_d, s_r) \\ t_d = 0.1x \quad x = 0, 1, 2, \dots \\ t_d < t_p \\ s_r = 0 \text{ or } 1 \end{cases} \quad (2)$$

Where  $f_h$  is the trajectory height of the fully opened parachute.  $t_d$  is the delay ignition time interval of roll rocket.  $s_r$  is the main rocket switch.  $t_p$  is the parachute opening time.

In view of the specific characteristics of the optimization problem, the custom optimization algorithm calculation process of the is shown in Fig. 3. The calculate process as shown in Fig. 3, can determine the optimal control parameter in a fixed ejection state. Using the batch command method, the optimal control parameters corresponding to 164 sets of ejection state parameters are calculated in batches, that is, the discrete control law point set.

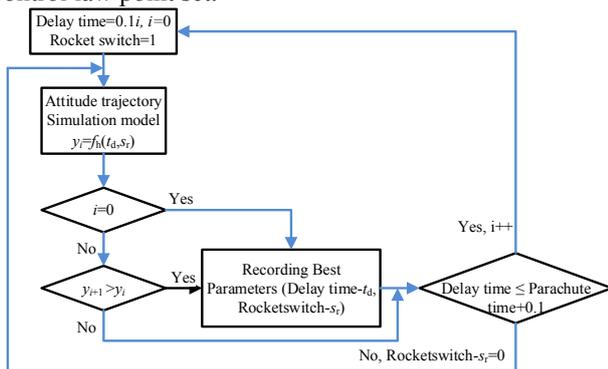


Figure 3. Flowchart of optimization algorithm

### 4.3 Neural network model

In order to obtain the continuous nonlinear mapping relationship between state parameters and control parameters, and ensure certain fault tolerance and self-adaptability, this paper uses the method of neural network model. BP (Back Propagation) network is widely used in function approximation, pattern recognition and so on [9]. In the previous research, the author also used BP neural

network to establish the mapping relationship between ejection overload and ejection velocity [10-11].

The model uses two neural networks. Network 1 is responsible for the pattern recognition of the main rocket switch, and network 2 is responsible for completing the non-linear mapping of the roll rocket delay ignition time. When network 1 determines that the value is 0, that is, the main rocket pack is shut down, then the Network 2 is no longer required to process the calculation.

Network 1 and Network 2 use the same neural network structure, and the number of network layers is two. The first layer is the input layer neurons, and 50 neurons. The second layer is the output layer neurons, and 1 neuron. The input vector is a two-dimensional vector corresponding to the ejection velocity and the roll attitude angle. The output vector is one-dimensional, the network 1 outputs the state of main rocket, and the network 2 outputs the delayed ignition time of roll attitude. The specific neural network structure is shown in Fig. 4

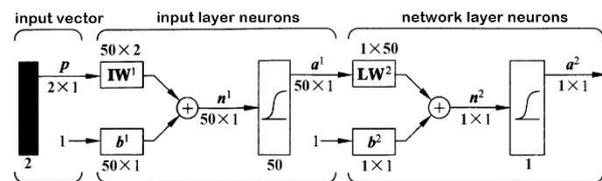


Figure 4. Structure of neural network.

The neural network is trained by using the sample point set of discrete control law calculated in the 4.2 section. Due to different functions, according to relevant experience, neural network 1 uses RPROP training algorithm, neural network 2 uses LM algorithm. The neural network processing process is shown in Fig. 5.

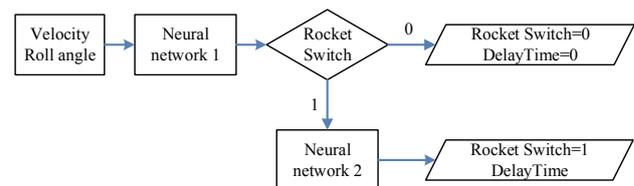


Figure 5. processing flowchart of neural networks.

## 5 Results

The trajectory curves under three different conditions, one without attitude control program, one with the control law raised in this paper and one with the multi-mode control law are shown in Fig. 6. Due to space limitations, only the results of ejection on 400 km/h are shown, and the roll angles are 45°, 90°, 120° and 180°.

When the roll angle is 45°, as shown in Fig. 6 (a), due to the unreasonable parameters of the delayed ignition time of the roll attitude rocket in the multi-mode control law, the roll attitude of the ejection seat is insufficiently corrected. However, after using the control law of this paper, the ejection trajectory height has been improved obviously, which shows that the effect of transverse roll attitude correction is remarkable.

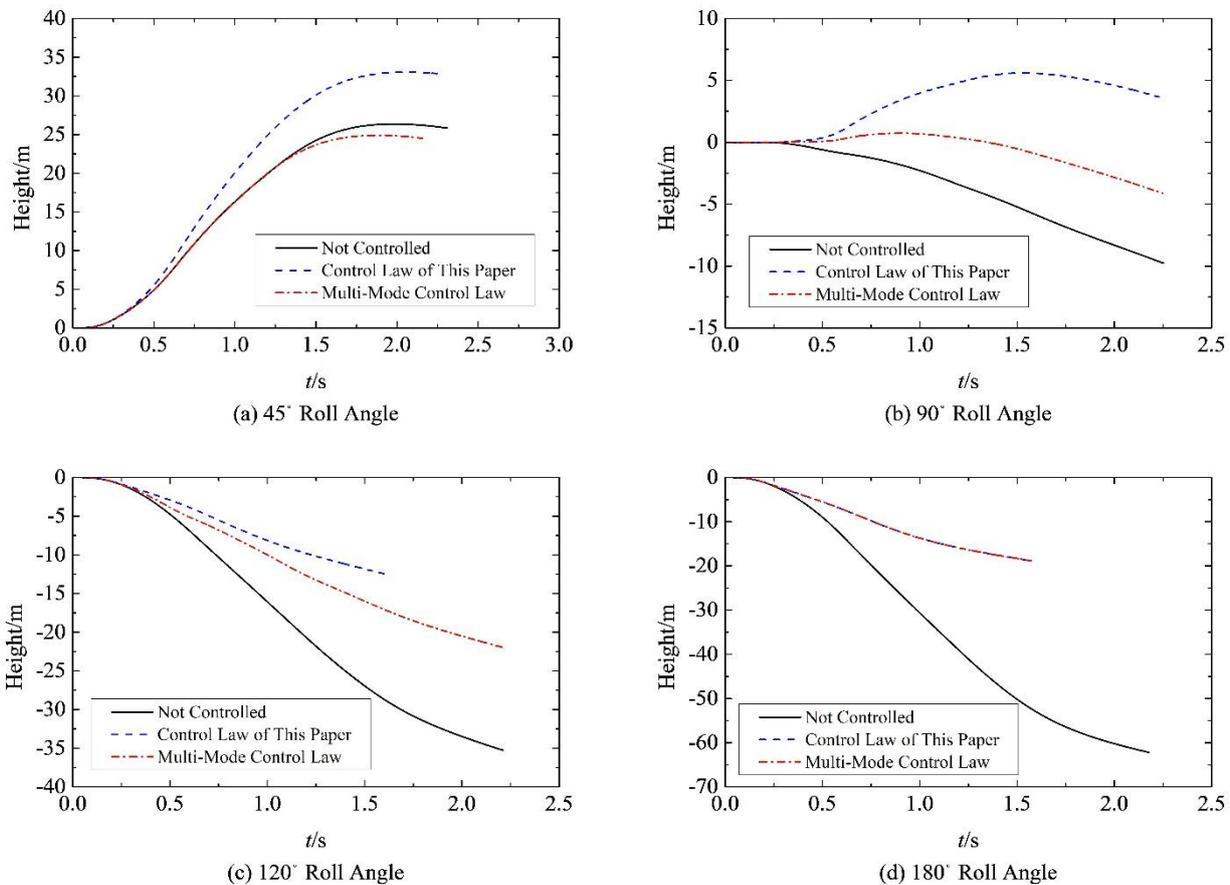
When the roll angle is  $90^\circ$ , as shown in Fig. 6 (b), the multi-mode control also plays a role in the adjustment of the track attitude. But compared with the control law of this paper, the effect is still insufficient. It is demonstrated that the control parameters obtained by the control law in this paper have better performance for the adjustment of the posture trajectory.

When the roll angle is  $120^\circ$ , the key of the control law at this time is to judge whether the main rocket is shut down. When the roll attitude Adjustment rocket has been unable to adjust the roll angle to positive in time and effectively, it is necessary to shut down the main rocket opening, thus avoiding the loss of safe height caused by the main rocket. It can be seen from Fig. 6 (c), the control parameter given by the multi-mode control law is the

rocket still working. But the result given by this paper is shutting down the rocket. It can be seen from the trajectory curve that the judgment result given by the control law in this paper is obviously more accurate.

When the roll angle is  $180^\circ$ , as shown in Fig. 6 (d), the control parameters given by the both control laws are identical.

In summary, the control algorithm obtained in this paper is better than the multi-mode control law in correcting the trajectory height. Whether in the optimality of the delay ignition time parameter of the roll attitude rocket or the critical value judgment of whether the main rocket is shut down, the control law algorithm obtained in this paper has better performance.



**Figure 6.** Comparison of ejection height under different control law at 400 km/h.

## 6 Conclusions

The design method of ejection seat control law proposed in this paper is feasible, the design process is simple and clear, and the result algorithm is easy to be realized.

The BP neural network model can well deal with the continuous nonlinear mapping problem and pattern recognition problem in the control law algorithm. The final result is very close to the theoretical optimal value and has fault tolerance.

Taking the roll adverse attitude ejection as an example, the design verification of the control law is carried out. It can be seen that the control law algorithm obtained in this

paper has outstanding control effect by comparing with the multi-mode control results.

Need to further study the control program and control law in diving, sinking and other adverse attitudes. Meanwhile, optimize calculation of the parachute opening time.

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