Design and Analysis of All-electric Aircraft Nose Wheel Steering System Based on Intelligent Algorithm

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Abstract. As all-electric aircraft has many advantages, aircraft nose wheel steering system would be developed to the all-electric direction. Aiming at the control demand of nose wheel steering system, based on the basic principles of nose wheel steering system and the design technique of mechatronics, an all-electric aircraft nose wheel steering system composed of a nose wheel steering mechanism of two worm gear and a control servo system of fly-by-wire having both steering and anti-shimmy function is designed to meet the demand for operation control in nose wheel steering system. Besides, the fuzzy algorithm and BP neural network algorithm is applied to the control system to explore its algorithm. Then based on Matlab/Simulink and LMS/AMESim software, the united simulation model of the system with fuzzy PID controller is established to make the dynamic simulation analysis for the verification of its steering function, the research results indicate that the nose wheel steering system is reasonable and validated, can meet the requirements of the general project.

Introduction

More electric aircraft takes electric power system as its second power as much as possible by using it to replace the original hydraulic, pneumatic and mechanical system [1, 2], as a result, it has the characteristics of simple structure, light weight, high reliability and high ratio of performance to price [3-5]. For the insurmountable and inherent defects of the hybrid system in current aircraft, the aircraft maintenance caused by such relevant system is accounted for more than 50% of the total aircraft maintenance. However, all-electric system has high reliability, high maintainability, low security and operating cost, and many other inherent advantages, the nose wheel steering system would be developed in the all-electric direction [6]. The realization of all-electric aircraft depends on whether the aircraft function subsystem using the electric power as its power can be developed. The realization of the all-electric nose wheel steering system would make the overall aircraft performance to be more perfect, and make a certain contribution to speed up the process of aircraft being all-electric. At present, the electric power systems used for flight control, environmental control, brake, fuel and engine starting system have been verified [6]. European scholars have begun to research the all-electric nose wheel steering system [7-9], whose results haven't announced to the outside, but they calculate the all-electric would increase significantly the levels of reliability and availability, besides, the coordination and cooperation between the all-electric nose wheel steering system and automatic ground navigation system would increase the air transport system efficiency. So whether to our civil aircraft or military aircraft, the realization of the all-electric nose wheel steering system has a certain significance to improve the ground operating performance.

An all-electric aircraft nose wheel steering system composed of a nose wheel steering mechanism of two worm gear and a control servo system of fly-by-wire having both steering and anti-shimmy function is designed in this article, Then the Fuzzy algorithm and Back-propagation (BP) neural network algorithm is applied to the control system to explore its algorithm. At last, the system’s
A united simulation model is established to make the dynamic simulation analysis for the verification of its steering function.

**The Design of the Nose Wheel Steering System**

**The Overall Scheme Design**

The nose wheel steering system belongs to the electromechanical actuator system which is the general name for the position servo control system in aviation and aerospace, military, transportation, agricultural and industrial machinery and equipment and controls the movement of its load directly or indirectly through controlling the operation of motor [10]. It is composed of two main parts: the actuator module and the electric control unit.

**The Actuator Module**

The actuator module is responsible for converting electrical energy into mechanical energy and feeding back the mechanical transmission to control system. In order to improve its reliability and availability, the mechanical transmission system with dual redundancy heat backup is selected, which require any single redundant failure wouldn’t influence the normal work of the system. As two channels are exactly the same, only the design of single redundant channel is illustrated. The diagram of the single redundant channel in steering system is shown in Fig. 1, as can be seen from the figure, It is composed of a motor, a torque limiter, a clutch, a reducer, a damper, a worm gear and sensors. In the process of aircraft steering on ground, the controller would firstly control the motor rotation according to the input signal, then the motor would transmit its torque to the torque limiter, reducer and clutch successively, as a result, the worm gear begin to rotate to realize the aircraft nose wheel steering. Its main components are described below:

![Figure 1. The diagram of the single redundant channel in steering system.](image)

**The Electronic Control Unit**

The Electronic control unit is responsible for position servo control and completing the closed loop of the nose wheel steering system, which is composed of the main controller and the motor controller.

According to the content above, the assumption diagram of the controller is available, as shown in figure 2. As can be seen from the figure, the main controller adopts similar dual redundancy design, two channels communicate with each other through the dual port of RAM and detect faults through cross supervision and self-supervision. In the process of nose wheel steering, the main controller would firstly make logical judgments according to digital signals to judge whether the system is in hand wheel operating mode or pedal rudder operating mode. Then the main controller would acquire such analog signals as command signal, feedback signal and the aircraft ground speed and carry on the data processing according to a certain control algorithm and control rate. Finally, the nose wheel steering servo control would be realized.
The Main Parameters’ Determination of the Transmission Component

Based on the aircraft nose wheel steering system design index [11, 12], the maximum steering torque, the maximum steering angle and the maximum steering speed provided by the nose wheel steering system are set to 7000N.m, 80 degrees and 0.349rad/s respectively.

Considering the commonly used motor speed, reducer transmission ratio range and Worm gear transmission ratio range, refer to the relevant design handbook, the motor model, the transmission ratio of the reducer and worm gear can be obtained respectively. Then the main transmission components of the nose wheel steering system are designed concretely according to the Handbook of mechanical and electric design. Finally, the main parameters of these transmission components are obtained, as shown in Table 1.

Table1. The main parameters of the transmission component in system.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>value</th>
<th>Parameter</th>
<th>value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Motor rated power</td>
<td>3.5kw</td>
<td>Worm gear number of teeth</td>
<td>53</td>
</tr>
<tr>
<td>Motor rated torque</td>
<td>34.3N.m</td>
<td>Worm gear module</td>
<td>12.5</td>
</tr>
<tr>
<td>Motor rated speed</td>
<td>1000r/min</td>
<td>Worm gear diameter coefficient</td>
<td>7.2</td>
</tr>
<tr>
<td>electro mechanic time constant</td>
<td>27ms</td>
<td>Worm gear gear center distance</td>
<td>376.25mm</td>
</tr>
<tr>
<td>reducer Drive ratio</td>
<td>5.66</td>
<td>Worm gear diameter</td>
<td>90mm</td>
</tr>
<tr>
<td>Worm gear gear drive ratio</td>
<td>53</td>
<td>Worm gear wheel diameter</td>
<td>662.5mm</td>
</tr>
<tr>
<td>Worm gear tooth profile angle</td>
<td>20</td>
<td>Worm gear end efficiency</td>
<td>0.94</td>
</tr>
<tr>
<td>Coefficient of top clearance</td>
<td>0.2</td>
<td>Worm gear material</td>
<td>40cr</td>
</tr>
<tr>
<td>addendum factor</td>
<td>1.0</td>
<td>Worm gear wheel gear material</td>
<td>ZCuSn6Pb6Zn3</td>
</tr>
<tr>
<td>number of threads</td>
<td>1</td>
<td>Worm gear gear efficiency</td>
<td>0.74</td>
</tr>
<tr>
<td>Converter amplification coefficient</td>
<td>40</td>
<td>current international coefficient</td>
<td>15</td>
</tr>
<tr>
<td>Electromagnetic time constant</td>
<td>0.0038s</td>
<td>Speed proportional coefficient</td>
<td>30</td>
</tr>
<tr>
<td>Converter delay time</td>
<td>0.00012s</td>
<td>Speed international coefficient</td>
<td>4</td>
</tr>
<tr>
<td>Input signal limit value</td>
<td>10V</td>
<td>Current proportional coefficient</td>
<td>0.1</td>
</tr>
<tr>
<td>Speed feedback coefficient</td>
<td>0.01</td>
<td>Current feedback coefficient</td>
<td>0.45</td>
</tr>
</tbody>
</table>
The Algorithm Research of the Nose Wheel Steering System Controller

The main controller of the aircraft nose wheel steering system is required to be able to process various data rapidly and real-time in the process of aircraft ground maneuver and realize the nose wheel steering in the guarantee of accuracy. The typical features of the aircraft nose wheel steering system are low damping, nonlinear, time-varying and terrestrial interference, as a result, traditional PID controller do not always achieve the most ideal control effect. With the research and application of fuzzy logic algorithm and neural network in recent years, the two algorithms began to be combined with PID control so as to improve the performance of traditional PID control. At present, the combination of the two intelligent algorithms and PID control has achieved a certain research results [13-15].

The Research of the Fuzzy PID Control with Self-adjusting Parameters

The schematic diagram of the fuzzy PID control system with self-adjusting parameters is shown in Fig.3, the three control coefficient of controller $K_p$, $K_i$ and $K_d$ is regulated by 3 two-dimensional fuzzy controllers FC1, FC2 and FC3. In the system working process, the controller would do such a series of operation as fuzzification, fuzzy logic reasoning and defuzzification according to the deviation $e$ and deviation change rate $ec$ of the system. Thus, parameters of the controller would be regulated instantaneously to achieve good control effect.

Based on the fuzzy control module of MATLAB and Simulink software platform, the fuzzy control simulation model of the nose wheel steering system is established. Then the step response signal $r_1(t)=1$ is selected to run simulation, the step response curve under the PID control and the fuzzy PID control with self-adjusting parameters can be obtained, as shown in Fig. 4. As can be seen from the figure, under the control of self-adjusting fuzzy-PID, the overshoot of the step response curve is almost 0 and the system adjusting time is 0.1s, both of whom have a larger decline relative to PID control’s. Meanwhile, it can be seen that the two curves are almost coincident after 0.4 seconds. From this it follows that compared with normal PID controller, self-adjusting fuzzy PID controller ensures the steady state performance of the system in addition to improve the dynamic performance of the system well, which could obtain good control effect.

Changing the system input to sinusoidal signal $r_2(t)=20\sin(2\pi t)$ to test the fast following performance of the system, Fig. 5 and Fig. 6 show the sinusoidal response curve of the system input and output under PID control and self-adjusting fuzzy PID control respectively. It can be seen that,
both the system input and output curves of the two control system have high coincidence degree, however, it is obvious that the system input and output curves in Fig. 11 are almost completely overlap, that is to say, the self-adjusting fuzzy PID control system has better following performance.

Figure 5. The sinusoidal response of input and output under PID control.

Figure 6. The sinusoidal response of input and output under self-adjusting fuzzy PID control.

The Research of the Parameters Self-adjusting PID control Based on BP Neural Network

The self-adjusting parameters PID control system based on BP neural network is shown in Fig.7. It consists of a BP neural network algorithm module and a PID controller. According to the operating conditions of nose wheel steering system, the neural network would adjust proportional, integral and differential coefficient of PID controller instantly for the realization of system performance optimization. That is to say, the output layer neuron of neural network is assigned to the three main control parameters of the PID controller, through the network learning and adjustment of weight coefficient, the PID controller parameters would follow the optimal control law of neural network finally.

Figure 7. The self-adjusting parameters PID control system based on BP neural network.

Based on BP neural network PID control principle and MATLAB software, the system simulation program is compiled. Then the step response signal r1(t)=1 and sinusoidal signal
\[ r_2(t) = 20\sin(2\pi t) \] are selected as system input and run simulation respectively, the system input and output curves can be obtained, as shown in Fig. 8 and 9.

![Figure 8](image1.png)

**Figure 8.** The step response of input and output under the BP neural network PID control.

![Figure 9](image2.png)

**Figure 9.** The sinusoidal response of input and output under the BP neural network PID control.

It can be seen from the figure 8 that, under the control of BP neural network PID controller, the overshoot of the system is up to 60% and the system adjusting time is 0.4s, both of them have a larger incline no matter relative to the prior PID control system or the self-adjusting fuzzy PID control system. This is due to the normal PID controller has obtained parameters with good control effects through trial and error method. However, during the process of the BP neural network PID controller solving the optimal PID control parameters, the performance of control systems may not be very good. As a result, neural network needs a certain amount of time to make the parameters of PID controller follow some optimal control law by self-learning and adjustment of weight coefficients. It can be seen from the Fig.9 that, as the sinusoidal input signal have provided adjusting time for neural network, under the control of BP neural network PID controller, the coincidence degree of system input and output curves is very high, that is to say, the system has good following performance.

As we know from the above, the self-adjusting parameters BP neural network to make the parameters of PID controller in compliance with some optimal control law by self-learning and adjustment of weight coefficients. So when the system input contain mutant signal, the performance of the system is not satisfactory in the initial adjustment period. Thanks to the adjustment period wouldn’t be too long, once the controller obtain the control parameters in compliance with the optimal control law, both the dynamic performance and steady state performance of the system would be better than the normal PID controller’s. But apparently in this system, the comprehensive control effect of self-adjusting fuzzy PID control is better than the BP neural network PID control’s.

**The United Simulation and Analysis of the Nose Wheel Steering System**

Based on the MATLAB-Simulink and LMS-AMESim software, according to nose wheel steering system and self-adjusting fuzzy PID controller having been designed, the united simulation model of the nose wheel steering system is established, whose Electric control part is in Simulink software while mechanical part is in AMESim software, as shown in Fig. 10 and Fig. 11.
As shown in Fig. 12, being the relationship curve of the nose wheel steering system input and output changing with time. It can be seen from the figure that, compared with the input curve, the output curve has a certain lag in the whole dynamic process of nose wheel steering. This is because considering the moment of inertia of motor rotor and various gap and friction in the system in practice, the motor requires a certain amount of time to accelerate from rest to rotate with rated speed, and then the system input require the motor to keep run with its rated speed until it reach the maximum steering angle position, as a result, the output signal has been unable to keep up with the input signal. It can be obtained that the movement tendency of the system input and output curves are basically consistent, although there is a certain lag, but the lag time is less than 0.3 seconds and acceptable, which means the nose wheel steering system has good following performance.

As shown in Fig. 13, is the relationship curve of the steer angle and shaft speed of DC motor changing with time. It can be seen from the figure that, in the process of the nose wheel steering
mechanism moving from the zero initial position to the maximum steering angle position, the motor speed is accelerated from zero to the rated speed after 0.3 seconds, which is the main reason of the system output lagging behind system input. Then the motor keep rotating with rated maximum speed until the nose wheel reach the maximum angle of 80 degrees. Although the motor reverse under the influence of small amount of system overshoot, with the stop of the nose wheel steering mechanism, the motor changes its turning direction and reduces its speed to zero accordingly.

As shown in Fig. 14, is the relationship curve of the torque on worm gear mechanism and the friction torque caused by clutch and bearing changing with time, the $y_1$ in figure represents the torque on worm gear wheel, the $y_2$ represents the torque on worm gear, the $y_3$ represents the friction torque caused by clutch and bearing, it can be seen from the figure that, at the 2.00548 second time when the nose wheel is rotating with rated speed, the torque on worm gear wheel is 6999.98N.m, the torque on worm gear is 179.434N.m, so the efficiency of the worm gear for nose wheel steering is:

$$\eta = \frac{6999.98}{179.434 \times 53} \times 100\% \approx 74\% \tag{1}$$

The friction torque caused by clutch and bearing is 10.566N.m, so the Worm gear end efficiency is:

$$\zeta = \frac{179.434}{179.434 + 10.566} \times 100\% \approx 94\% \tag{2}$$

As shown in Table 1, the simulation results are the same as of the design results before, which means the model reflects the designed nose wheel steering system well and therefore the simulation results have certain reliability.

Figure 14. The relationship of torque on worm gear and friction torque caused by clutch and bearing.

Conclusions
An all-electric aircraft nose wheel steering system composed of a nose wheel steering mechanism of two worm gear and a control servo system of fly-by-wire having both steering and anti-shimmy function is designed in this article, and the algorithm research and simulation analysis of system have been finished, the results show that:

1. The design of the aircraft all-electric nose wheel steering system is reasonable and effective, which can meet the requirements of engineering application.
2. Compared with the conventional PID control, both of the self-adjusting fuzzy PID control and the self-adjusting BP neural network PID control have their advantages, but the comprehensive control effect of the self-adjusting fuzzy PID control is better than the self-adjusting BP neural network PID control.
3. The nose wheel steering system is able to achieve the steering function of large angle with its expected maximum speed.
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References


