Application of two-phase hybrid stepping motor based on three-phase inverter chopping control strategy in aircraft electric drive servo valve

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Abstract. With the development of multi-/all-electric technology, more and more aircraft platforms use electrically driven servo valves as the driving source to realize real-time adjustments of flow, pressure and temperature in the area network. The new generation of aircraft applies a stepper motor to drive the servo valve as the drive source, and utilizes the holding torque and open-loop control characteristics of the stepper motor when the stepper motor could not meet aircraft's requirements of the reliability of the servo valve, the controllability of the opening and closing angle, and the environmental resistance. This paper develops a set of stepper motor drive servo valve control system. The system is mainly composed of flight tube bus, electromechanical management computer, remote actuation unit, remote interface unit and motor-driven servo valve. The stepper motor driver is integrated in the remote execution unit and is used to control the two-phase hybrid stepper motor to drive the servo valve. The topology of a three-phase inverter bridge drive is used to achieve the two-phase double four-shot drive, which saves about 25% power drive hardware. By controlling the two-phases motor, the direction and amplitude of the current one can realize micro-step control. The test and simulation result show that the system has higher control accuracy and better acceleration. The deceleration characteristics in two-phase full step and micro step working modes can expand the application of electric servo valve and improve aircraft performance.

1. Introduction
As the development of multi-/all-electric technology, there is an increasing number of aircraft platforms that use electric drive servo valves as the driving source to realize real-time adjustments of flow, pressure and temperature of aircraft fuel, hydraulic, environmental control and other systems [1]. Most traditional electric drive valves utilize ordinary brushed DC motors or brushless DC motors as the drive source. However, Brushed DC motors have low control accuracy with shorter life [2]. The new generation of aircraft uses a stepper motor to drive servo valve as the drive source, and utilizes the holding torque and open-loop control characteristics of the stepper motor when the stepper motor stops to meet aircraft's requirements for the reliability of the servo valve, the controllability of the opening and closing angle, and the environmental resistance [3]. In this paper, a two-phase hybrid stepping motor driven servo valve is selected as the research object. Because of the low-frequency oscillation phenomenon that the stepping motor is easy to produce when the stepping motor rotates at a low speed, the micro-step control strategy is studied, and the topology of the three-phase inverter bridge drive is adopted. The test and simulation results show that the system is able to achieve higher control accuracy and better acceleration as well as deceleration under two-phase full-step and micro-
step working modes, which expands the application of the electric servo valve and improves the performance of aircraft.

2. System overall design
Figure 1 shows the block diagram of the servo valve control system, which is driven by the stepper motor. The system mainly includes the flight tube bus, the control computer (hereinafter referred to as CC), the remote interface unit (hereinafter referred to as RIU), the remote execution unit (hereinafter referred to as REU) and the electric drive servo valve. The whole aircraft is equipped with three CCs, ten RIUs and sixteen REUs. Each REU integrates two-way stepper motor interfaces. As the calculation center, CC mainly realizes calculations of temperature, flow, pressure and other signals, comparisons with the control target value, calculations of the control rate, and then outputs the number of rotation steps and the direction of the corresponding valve [4]. RIU is mainly responsible for the signal acquisition of regional temperature, flow and pressure. REU receives control commands issued by CC, and drives the stepping motor servo valve to rotate to achieve the established control goal. The system realizes the interconnection between the sub-systems through IEEE-1394, used to realize the deterministic delay of control commands.

3. Power-driven design
Figure 2 demonstrates a block diagram of the hardware architecture of the three-phase inverter. The stepper motor controller is integrated inside the REU. The system is mainly composed of a stepper motor controller, a three-phase power bridge, an inverse time protection circuit, a current monitoring circuit, and an output monitoring circuit composition. The stepping motor controller selects the TMS320F28335 motor dedicated controller, which is produced by TI, to receive control instructions and generate a fixed pulse sequence. The three-phase power bridge is composed of 3 groups of
"28V/open discrete output interface" and "ground/open discrete output interface" [5]. The upper bridge drive adopts the current protection method with inverse time characteristics. When the motor current is overcurrent, the trip signal is set, and then the REU main processor can obtain the motor overcurrent status by collecting the trip signal. The output monitoring adopts the configurable DEI1282 discrete acquisition chip to realize the BIT test function of the output state of the three-phase power bridge.

Figure 2. Diagram of the hardware architecture of the three-phase inverter.

4. The design of chopper control strategy for three-phase inverter

4.1. Micro-stepping control principle
When the two-phase hybrid stepping motor A and B are connected with a sine wave current, the electromagnetic torque is [6]:

$$T = k_T \cdot I_m \cdot \sin(\beta - \theta)$$

(1)

Where, T is the electromagnetic torque, $k_T$ the proportional constant, $\theta$ is the electrical angle position of the rotor, and $\beta$ is the electrical angle that the motor hopes to be set. The micro-step driving of the two-phase hybrid stepping motor is able to control the current one in two-phase windings, so that the synthesized magnetic field inside the motor is a circular space rotating magnetic field. The vector size of the synthesized magnetic field determines the motor torque, and the angle between two adjacent synthesized magnetic field vectors is the step angle after micro-step. In the dual four-beat control of a two-phase hybrid stepping motor, if the micro-step number is n, the motor needs to go through 4n states for every $2\pi$ electrical angle, and the step angle after micro-step is $\pi/2n$ [7]. Figure 3 illustrates the eight micro-step states current vector diagrams and two-phase current values.
Figure 3. Eight micro-step states current vector diagrams and two-phase current values.

4.2. The principle of three-phase inverter chopper control

The driver of the traditional two-phase hybrid stepping motor adopts a double H-bridge circuit, and each H full-bridge is connected to a phase winding, which means that every four MOS transistors can form a full bridge, and the on-off state of each bridge arm is complementary [8]. The control of a two-phase hybrid stepping motor is actually to control its current direction and current size. If the two-phase winding of the two-phase hybrid stepping motor is connected to the three-phase inverter bridge, the discrete electrical angle value is firstly passed, and then the direction of the rated current in the two-phase winding is judged, and subsequently, the two-phase current is sampled, which will be compared with the amplitude of the given reference value. Then, the current direction and the logical signal of the amplitude are input into the chopper switch selection state table, DSP. The IO port outputs 6 chopping signals to control the on and off situation of the 6 MOS tubes, saving nearly 25% power drive hardware, and has scalability [9]. Figure 4 demonstrates the principle block diagram of the open-loop vector micro-step control system.

Figure 4. The principle block diagram of the open-loop vector micro-step control system.

4.3. Current direction control

According to the AB phase current direction, there are four ways to energize: AA' and BB', AA' and B'B, A'A and B'B, A'A and BB', respectively. When two-phase windings of the motor are connected in series, the resistance and inductance are doubled, and the back electromotive force is also the vector sum of two opposite potentials [10]:

$$V_{fe} = [V_{ab} + V_{bc}] = R(i_a + i_b) + L\left(\frac{di_a}{dt} + \frac{di_b}{dt}\right) + K_e\theta_e\left(\sin \theta_e + \cos \theta_e\right)$$

(2)

When two-phase windings of the motor are connected in parallel, voltages at both ends of the windings are equal, which can be expressed by the following formula [11]:

$$V_{fe} = \left|V_{ab} + V_{bc}\right| = R(i_a + i_b) + L\left(\frac{di_a}{dt} + \frac{di_b}{dt}\right) + K_e\theta_e(\sin \theta_e + \cos \theta_e)$$

(2)
Where, $V_{DC}$ is the DC power supply, $V_{ab}$ and $V_{bc}$ represent the voltage across the two-phase windings respectively, $i_A$ and $i_B$ show currents in windings A and B. R and L are the winding resistance and inductance, $K_m$ is the torque constant of the motor, $\theta_e$ is the electrical angle of the rotor, $\omega$ is the angular velocity of the rotor. Figure 5 to 8 demonstrate motor winding connection modes under four energization modes. The series and parallel connection of two-phase windings have an impact on the back EMF.

4.4. Current amplitude control

The control of the current amplitude requires proper adjustment of the energized state of motor windings. That is, when the sampling current is less than the reference current, it is supposed to be a certain positive potential difference between two ends of the winding. At this time, the winding can be connected to both ends of the DC voltage alone, or it can be connected in parallel with another phase winding or connected in series to both ends of the DC voltage. When the sampling current is greater than the reference current, the potential difference between two ends of the winding is zero or negative, and meanwhile the winding enters the freewheeling phase [12].

When the two-phase hybrid stepping motor works in four energization modes, the current directions are AA’ and BB’, AA’ and B’B, A’A and B’B, A’A and B B’, respectively. In each current direction, according to the comparison between the current amplitude and the reference amplitude, the inverter bridge can work in 4 switching modes, and the inverter has 16 energization modes. The two-phase current of the motor is controlled through the look-up table 1. The two-phase hybrid stepping motor is supposed to work in the required working mode to reduce the torque pulsation.

| Current direction | Current amplitude control of phase A | Current amplitude control of phase B |
|------------------|------------------------------------|------------------------------------|
|                  | State of current | State of switches | State of current | State of switches |
| AA’ and B B’     | $i_A < i_{ref}$ | Q1 & Q6 ON | $i_B < i_{ref}$ | Q1 & Q6 ON |
| B                 | $i_A > i_{ref}$ | Q1 OFF       | $i_B < i_{ref}$ | Q3 & Q6 ON |
5. Design of chopper control software for three-phase inverter

Figure 9 illustrates the flow chart of the chopper control software for the three-arm chopper. The chopper control software of the stepper motor three-phase inverter is divided into the main program and the A/D interrupt service program. The interrupt service program includes the sine-cosine table generation subroutine, PI subroutine, dead zone compensation subroutine and PWM generation subroutine, and etc. Firstly, the main program initializes the system configuration register, clears all interrupt flags, sets IOPE1 to IOPE6 ports as ordinary I/O ports, sets corresponding ports of the control bridge arm down tube to zero, enables interrupt 1, and uses clock 1 underflow interrupt to initiate A/D sampling. After enabling the timer, it enters the loop waiting. When the timer has an underflow interrupt flag and the main program protects the scene, it enters the interrupt service routine. The software obtains the discretized rotor position based on the number of rotation steps, and calculates the A and B phase currents according to the value of the A/D sampling register. The system filters the current in the two-phase windings, judges the polarity of the two-phase reference current, and judges the relationship between the two-phase sampling current and the reference current modulus. The system selects the current chopping switch state according to the logical relationship shown in Table 1, sets the corresponding I/O port (high level or low level), and generates 6 PWM drive signals.

| Condition | Action |
|-----------|--------|
| $i_d < i_{\text{ref}}$ | Q1 & Q4 ON | $i_B > i_{\text{Bref}}$ | Q3 & Q6 OFF |
| $i_d > i_{\text{ref}}$ | Q1 & Q4 OFF | $i_B > i_{\text{Bref}}$ | Q3 & Q6 OFF |
| $i_d < i_{\text{ref}}$ | Q2 & Q3 ON | $i_B < i_{\text{Bref}}$ | Q3 & Q6 ON |
| $i_d > i_{\text{ref}}$ | Q2 OFF | $i_B < i_{\text{Bref}}$ | Q3 & Q6 ON |
| $i_d < i_{\text{ref}}$ | Q2 & Q3 ON | $i_B > i_{\text{Bref}}$ | Q6 OFF |
| $i_d > i_{\text{ref}}$ | Q2 & Q3 OFF | $i_B > i_{\text{Bref}}$ | Q6 OFF |
| $i_d < i_{\text{ref}}$ | Q1 & Q4 ON | $i_B < i_{\text{Bref}}$ | Q4 & Q5 ON |
| $i_d > i_{\text{ref}}$ | Q1 OFF | $i_B < i_{\text{Bref}}$ | Q4 & Q5 ON |
| $i_d > i_{\text{ref}}$ | Q1 & Q4 OFF | $i_B > i_{\text{Bref}}$ | Q5 OFF |
| $i_d < i_{\text{ref}}$ | Q2 & Q3 ON | $i_B > i_{\text{Bref}}$ | Q2 & Q5 ON |
| $i_d > i_{\text{ref}}$ | Q2 & Q3 OFF | $i_B < i_{\text{Bref}}$ | Q4 & Q5 OFF |
| $i_d < i_{\text{ref}}$ | Q2 & Q5 ON | $i_B < i_{\text{Bref}}$ | Q4 & Q5 ON |
| $i_d > i_{\text{ref}}$ | Q2 OFF | $i_B > i_{\text{Bref}}$ | Q4 & Q5 OFF |
| $i_d < i_{\text{ref}}$ | Q2 & Q3 ON | $i_B > i_{\text{Bref}}$ | Q4 & Q5 OFF |
| $i_d > i_{\text{ref}}$ | Q2 & Q3 OFF | $i_B > i_{\text{Bref}}$ | Q4 & Q5 OFF |
Initialize system and interrupts

Set some I/O ports low

Initialize event manager A, general timer 1 and 6 general I/O ports

Initialize the ADC unit

Initialize custom constants and variables

Enable timer 1

Loop waiting

INT1 interrupt

Protect the scene

Enter ADC interrupt service subroutine

Look-up table to get the subroutine of discrete angle

Current measurement value conversion subroutine

Judgment of current direction

Judgment of current

Look up the table

Set the corresponding I/O port

Clear the interrupt flag and restore the scene

Return

Figure 9. Open loop vector micro-step control software flow chart.

6. Experiment
The experiment utilizes a two-phase hybrid stepping motor. The working voltage is 28V, rotating step angle is 1.8°, rated static phase current is 3A, phase resistance is 0.35Ω, phase inductance is 1.6mH, holding torque is 1Nm, and moment of inertia is 0.2g.cm.s². Figure 10 and Figure 11 show simulation waveforms of the motor current and electrical angle in the MATLAB/Simulink simulation. Figure 10 illustrates the two-phase current and electrical angle simulation waveforms under the two-phase full-step working mode, while Figure 11 illustrates the two-phase current and electrical angle simulation waveforms under eight micro-step working modes. Figure 12 to 14 show simulation waveforms of the motor current and electrical angle in the experiment. To be more specific, Figure 12 illustrated the two-phase current test waveform under the two-phase full-step working mode, and Figure 13 shows
the two-phase current test waveform under the eight-division working mode and phase current test waveform. Figure 14 demonstrates the current waveform when the motor starts and accelerates. The simulation and experimental results mean that the micro-step control is able to obtain an approximate sinusoidal current waveform. With an increasing number of micro-steps increases, the current ripple is further suppressed, and the control strategy shows better acceleration performance.

Figure 10. Simulation waveform of two-phase current and electrical angle in two-phase full-step working mode.
Figure 11. Two-phase current and electrical angle simulation waveform in eight micro-steps working mode.

Figure 12. Two-phase current test waveform in two-phase full-step working mode (2A/div).
7. Conclusion

This paper develops a set of stepper motor drive servo valve control system. The system is mainly composed of flight tube bus, electromechanical management computer, remote actuation unit, remote interface unit and motor-driven servo valve. The stepper motor driver is integrated in the remote execution unit and is used to control the two-phase hybrid stepper motor to drive the servo valve. The topology of a three-phase inverter bridge drive is used to achieve the two-phase double four-shot drive, which saves about 25% power drive hardware. By controlling the two- phases motor, the direction and
amplitude of the current one can realize micro-step control. The test and simulation result show that the system has higher control accuracy and better acceleration. The deceleration characteristics in two-phase full step and micro step working modes can expand the application of electric servo valve and improve aircraft performance.

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