Application of Step Motor Servo Control Technology in Integrated Thermal Management of Advanced Fighter System

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Abstract. The integrated thermal management of advanced fighter jets directly affects the combat performance of the aircraft. This paper develops a set of multi-cycle integrated thermal management control system, based on the stepper motor drive servo valve. The stepper motor control system is integrated in the aircraft Remote Execution Unit (REU). The controlled information, such as flow, pressure, temperature, is collected and combined through the Remote Interface Unit (RIU). Through the IEEE-1394 bus, feedback achieves deterministic transmission between control-action-response, and through inverse time protection, the high reliable power drive can be achieved. The open-loop vector micro-stepping driving strategy of the stepper motor is designed, simplifying software and hardware designs. The experimental results show that the strategy developed in this paper can better realize the characteristics of two-phase current sine wave, have better acceleration performance, improve the controllability of the opening and closing angle of the stepping motor servo valve, and satisfy the comprehensive thermal management of advanced fighters.

1. Introduction

As the continuous improvement of the performance of advanced fighter jets, a large number of highly integrated electronic equipment has been comprehensively applied, and the heat load generated by the power system, power supply system, and hydraulic system has continuously increased its heat dissipation requirements [1]. At the same time, with the integration and compactness of fighter aircraft design, a large number of heat sources are encapsulated in a small space. The surface of the aircraft fuselage is often made of composite materials with poor thermal conductivity to reduce weight [2]. The number of openings on the outer surface of the aircraft should be reduced as much as possible. The area is required to achieve stealth and drag reduction. The above factors limit the ability of advanced fighter jets to dissipate heat through convection between the surface and the outside air. Meanwhile, during the flight mission cycle of advanced fighters, there are some uncertainties in the timing and magnitude of heat sources, generated by the multi-mission system, scattered heat sources, and limited heat sink resources, posing great challenges to the comprehensive thermal management of advanced fighters [3].

Integrated thermal management includes rational utilization, distribution and schedules of heat and heat sinks. With the development of comprehensive and effective control technology, comprehensive utilization and management of energy and heat sinks can be realized by efficient heat collection, transmission and dissipation methods. The advanced fighter, integrated the thermal management technology, is mainly applied to the cooling subsystem of the aircraft ring control and to the thermal load subsystem of the fuel system to realize heat management of the entire aircraft. Air forced cooling is usually applied to key electronic equipment, liquid cooling is usually used in high heat flux and
high-power task electronic equipment, and liquid cooling heat transfer methods are applied to power systems and hydraulic systems[4]. The traditional liquid cooling control valve generally takes a brushed DC motor as the drive. However, the life-cycle of this is short and its control accuracy is low, which limits the high-precision closed-loop application of the valve. The new generation of electric valve utilizes brushless motor as drive, but the control is complicated and the control accuracy is not high at low speed. According to the advanced fighter's servo valve reliability, opening and closing angle controllability and environmental requirements, the system uses a stepper motor as drive source, and adopts an incremental control method based on rotation speed and superheat to ensure that the refrigerant flow can meet requirements [5]. In this paper, the inherent low-frequency oscillation and overshoot of the stepper motor are studied, and an open-loop vector micro-stepping driving strategy for a two-phase hybrid stepping motor is designed. The stator magnetic field position information is obtained by open-loop cumulative rotation steps. Form a single current closed loop the control accuracy of the stepping motor is improved and control requirements of the advanced fighter integrated thermal management of the servo valve is fulfilled through the synthesis of current vector and discrete positioning angle value, which simplifies software and hardware designs.

2. System overall design

Figure 1 shows the architecture diagram of the multi-cycle heat integrated control system, which realizes real-time control of the system’s heat dissipation flow by temperature-flow coupling control method. After pressurized by the fuel pump, the high-pressure fuel flows through the heat exchangers, after which it passes through the fuel supply pipe and enters the fuel pump again, forming an internal circulation. Through the internal circulation, the fuel supply temperature is continuously increased, so that the engine reaches the highest temperature. Fuel returns to the front fuel supply tank all the way through the system to ensure that the fuel supply temperature of the engine does not exceed the limit of the engine. When the system temperature exceeds the high temperature threshold, the stepper motor is controlled to increase the opening of the flow valve, and consequently to increase the fuel flow, and the heat dissipation capacity, thereby reducing the system temperature. When the system temperature is lower than the low temperature threshold, the stepping motor is controlled to achieve the flow valve. The opening degree is reduced to decrease the fuel flow, and as a result the engine consumes high-temperature hot oil as much as possible, and therefore the heat taken away by the engine's fuel consumption is increased. The stepping motor servo control system is integrated in the aircraft Remote Execution Unit (REU). The whole machine is equipped with sixteen REUs. Each REU is equipped with two stepping motor interfaces, which are distributed on the front fuselage, middle fuselage and Rear fuselage. By the IEEE-1394B bus interface, REU receives control instructions issued by the Vehicle Management Computer (VMC), to generate a fixed pulse sequence, drive the motor to rotate to a predetermined position, realize the control of the valve opening angle, and adjust the flow, pressure, as well as pressure of network nodes. The flow, pressure, temperature and other information of the aircraft's regional network nodes are collected through the Remote Interface Unit (RIU) and uploaded to the flight control computer by the IEEE-1394B bus to be included in the closed-loop control. The entire aircraft is equipped with eight RIUs to participate in the integrated heat and management of the closed-loop control system.
3. Highly certain and reliable hardware architecture design

3.1. High-reliability network transmission delay design

The system uses IEEE-1394 bus network to realize the information exchange among sixteen REUs, ten RIUs and three VMCs. The IEEE-1394 bus adopts the basic topological structure with loops, and different REU, RIU, as well as VMC to form multiple loops, so that the system is able to deal with one-time disconnection. The IEEE-1394 bus uses pre-allocated bandwidth technology to improve the certainty of data transmission. Each node is allocated with a fixed transmission offset, reception offset and data offset in advance, and each node is planned in advance to arrive at the time of the transmission offset[6]. The number and size of asynchronous stream packets should be sent at the time, while each remote node changes its own predefined time offset according to the asynchronous stream packet tail information sent by the bus controller node in the first bus cycle. The communication sequence is reasonably arranged to ensure that the key data has a deterministic time delay that can be designed during the transmission process. Take the stepping motor control process in REU as an example. Assuming that the time RIU takes time from collecting flow pressure information to complete asynchronous flow packet grouping is $\Delta T_1$, and VCM takes time from receiving RIU data to complete instructions for steering, speed, and rotation steps. $\Delta T_2$ means the time REU takes from receiving the VMC instruction to the start of drive the actuator $\Delta T_3$. By reasonably designing the time offset of RIU, CC and REU, the corresponding time delay of the motor control instruction in the electromechanical system is controlled within $(\Delta T_1+\Delta T_2+\Delta T_3+2*\Delta T_4)$. Figure 2 shows the architecture diagram of the multi-cycle integrated thermal management control system.
3.2. Highly reliable power drive design

When the hardware circuit is abnormal or the motor load is short-circuited, stepper motor interface overcurrent and short circuit protection can prevent damage from motor and controller. In the double H-bridge power drive of the stepping motor, the output of the upper bridge arm performs the overcurrent point anti-delay shutdown protection according to the load characteristics [7]. Figure 3 illustrates the block diagram of the inverse time protection of the upper arm power circuit. The inverse time protection controller obtains the load current by a sampling resistor, and simulates the high-order inverse time protection curve in a segmented manner. The inverse time limit energy accumulation calculation is realized by looking up the table to determine the off time. In the energy accumulation calculation, a fixed step is used as the energy accumulation value. When the energy accumulation value reaches the specified threshold, the output is turned off, a trip signal is issued, and the hardware is placed in a safe state until the REU main controller releases the trip signal.
The general mathematical model form of inverse time limit protection is:

\[ t = \frac{k}{\left( \frac{I}{I_p} \right)^r - 1} \]  

(1)

Where, \( I \) and \( I_p \) represent the sampling current and the protection starting current respectively, \( r \) and \( k \) are constants, in which \( r \) takes a value between 0 and 2, and the dimension of the \( k \) value is time.

Inverse time protection data processing methods mainly include direct data storage method and curve fitting method [8]. In this paper, direct data storage method is used. According to the sampling current value, the corresponding time can be obtained by looking up the table. The realization method is shown in figure 4. The action relationship between the inverse time protection time \( t \) and the current is:

- \( I/I_p = 1 \), means that the protection does not operate;
- \( I/I_p < 1 \), means that the protection does not operate;
- \( I/I_p > 1 \), indicates that the protection will operate. The larger the protection is, the shorter the protection operation time is.
4. The design of open-loop vector micro-stepping control strategy

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 calculated, and when the iron core saturation effect are ignored and the high-order harmonic effect in the main permeance is ignored, the moment angle characteristic is a sine wave[9]:

$$T = k_T \cdot (-I_a \sin \theta + I_b \cos \theta)$$ (2)

Where, $k_T$ represents the constant of proportionality, and $\theta$ represents the electrical angle position of the rotor.

If the A and B phase windings are supplied with the following currents:

$$\begin{cases} I_a = I_m \cdot \cos \beta \\ I_b = I_m \cdot \sin \beta \end{cases}$$ (3)

Where, $\beta$ means the electrical angle that the motor hopes to position. After substituting the torque expression, the torque is expressed as:

$$T = k_T \cdot I_m \cdot \sin(\beta - \theta)$$ (4)

It can be seen from the torque equation that the micro-stepping driving of the two-phase hybrid stepping motor is to control the current in the two-phase windings, so that the synthesized magnetic field inside the motor is a circular space rotating magnetic field[10]. The ideal A and B phase currents are sine waves and the sine waves are fitted by multi-step waves to achieve the control effect of constant torque amplitude. The vector size of the synthesized magnetic field determines the torque of the motor. The angle between two adjacent synthesized magnetic field vectors is the step angle after micro-stepping. One tooth pitch of the two-phase hybrid stepping motor is $2\pi$ electrical angles. In the full-step operation mode, the motor needs to go through 4 state switching for every $2\pi$ electrical angles. If the micro-stepping number is $n$, the motor needs to go through $4n$ states for every $2\pi$ electrical angle, and the step angle after micro-stepping is $\pi / 2n$. Figure 5 demonstrates the eight micro-step states current vector diagrams and two-phase current values.
4.2. Closed-loop micro-stepping control strategy design

The traditional micro-stepping drive of a two-phase hybrid stepping motor is to store the subdivided two-phase current value in EPROM, obtain motor rotation steps, steer and speed control signals through the microprocessor, and take out the reference current value from the EPROM[11]. The magnitude is subtracted from the actual two-phase current value obtained by the A/DC sampling of the microprocessor respectively, and the difference is modulated by the PID link. The modulation value is compared with the triangular carrier, and a PWM wave is generated to control the on and off of each power tube. This control strategy adopts dual current closed-loop control. A and B phases are completely symmetrical, and each unit module requires two. Figure 6 shows a block diagram of traditional software to achieve micro-stepping control. The realization of the entire system is relatively complicated, and PID parameters need to be set for different motors[12]. The software portability and consistency are poor, which triggers greater challenges to the design of the control system.

4.3. Open-loop vector micro-stepping control strategy design

The open-loop vector means that the electrical angle value, representing the position of the stator magnetic field, is not obtained in a closed-loop way, but is obtained in an open-loop way of accumulating the number of rotation steps [13]. Figure 7 illustrates the principle block diagram of the open-loop vector micro-stepping control system. After the two-phase winding current is sampled and modulated, it is sent to the A/D sampling port of the microprocessor, and the microprocessor performs software filtering and calculation on the sampled current. The amplitude of the synthesized current space vector is obtained and compared with the given current. The difference is modulated by the PI
According to the motor positioning requirements, discrete electrical angle values of the sine and cosine waves are obtained, and sine and cosine values are multiple with $V_p$ respectively to obtain A and B phase modulated signals of $V_a$ and $V_b$. In order to prevent the same bridge arm from being through, the dead time is added to complement two PWMs. To ensure the accuracy of the control signal, the dead time is compensated at the same time to obtain modulation signals of $V_a'$ and $V_b'$ after the dead time compensation. Through micro-processing, eight unipolar PWM modulation waves are generated to control the on and off of the MOS tube of the H bridge.

$$I_p = \sqrt{I_a^2 + I_b^2}$$

\[ V_a = V_p \cdot \cos \theta_{disc} \quad V_b = V_p \cdot \sin \theta_{disc} \]

**Figure 7.** The principle block diagram of the open-loop vector subdivision control system.

### 5. Design of Open-loop Vector micro-stepping Control Software

The stepper motor open-loop vector micro-stepping control software is divided into the main program and the A/D interrupt service program. The interrupt service program includes sine cosine table generation subroutine, PI subroutine, square root subroutine, dead zone compensation subroutine and PWM generation. Firstly, the main program initializes the system configuration register, enables the first-level interrupt INT1, and uses the clock 1 underflow interrupt to start A/D sampling. When the underflow interrupt flag appears on the clock, the microprocessor samples A and B phase currents. The A/D interrupt service program is entered to calculate the sum of squares of A and B phase current values, solving the square root, and getting the combined current $I_p$. In the angle discretization program, look up the table of the current step number to get corresponding sine and cosine values. The two-phase modulation signal is calculated by using the given voltage signal and the discrete angle output in the PI link. The dead zone compensation is performed on the modulation signal to obtain a unipolar PWM modulation wave. The PWM modulation wave adopts a constant frequency pulse width modulation chopping method. To avoid the direct connection between the upper and lower pipes of the same bridge arm, the dead zone time and dead zone compensation time are set at the same time. **Figure 8** shows the flow chart of the open-loop vector micro-stepping control software.
6. Experiment

The experiment adopts a two-phase hybrid stepping motor with a rated phase current of 3A, a power supply voltage of 36V, a phase resistance of 0.35Ω, a phase inductance of 1.6mH, and a step angle of 1.8°. In the experiment, the step angle is subdivided into various steps to verify the effect of micro-stepping. Figure 9 demonstrates the two-phase winding current waveform in the four-division state, Figure 10 shows the two-phase winding current waveform in the eight-division state, and figure 11 illustrates the two-phase winding current waveform in the sixteen-division state. As the number of micro-stepping increases, phase current fluctuations become smaller. Figure 12 shows that during the acceleration of a two-phase hybrid stepping motor, the two-phase current waveform of the motor presents a better sine wave and has a better acceleration performance.

Figure 8. Open loop vector subdivision control software flow chart.
7. Conclusion
In this paper, based on stepper motor driven servo valve, a set of multi cycle integrated thermal management control system is developed. The stepper motor control system is integrated into the aircraft remote actuator. The controlled information, such as flow, pressure and temperature, is collected and feedback through the remote interface unit and the deterministic transmission between control actions driving of power is realized by inverse time limit protection. The open-loop vector micro-stepping driving strategy of stepping motor is designed, which simplifies the design of software and hardware. The experimental results show that the strategy developed in this paper can better realize the sine wave characteristics of two-phase current, with better acceleration performance. It improves the controllability of opening and closing angle of stepper motor servo valve, and meets control requirements of advanced fighter integrated thermal management.

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