GRAVITY MEASUREMENT METHOD OF SOLID ROCKET DRIVE BASED ON SWITCHED RELUCTANCE MOTOR SYSTEM

by

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Solid rocket drive system based on switched reluctance motor is established through the working principle of switched reluctance motor, and the closed-loop precise control of solid rocket drive system digitization is realized by the control method of pulse width modulation technology. The gravity value of solid rocket drive system is measured by the vertical deviation measurement method based on attitude error observation. The attitude datum of solid rocket drive system is obtained by the relationship between the vertical deviation and the attitude error of solid rocket drive system. The state space of solid rocket drive system is established by the attitude datum obtained. The horizontal gravity component estimation model of the real gravity value of the solid rocket drive system is established by the state space model, and the accurate gravity value of the solid rocket drive system is obtained by the estimation model. The simulation results show that the method can effectively measure the gravity value of solid rocket driving system, and the errors of measuring the gravity of solid rocket driving system are less than 1%.

Key words*: switched reluctance motor system, rocket engine, driving coefficient, gravity value*

Introduction

Switched reluctance motor (SRM) is a kind of motor based on variable reluctance principle. In recent years, due to its strong structure and no need for permanent magnetic materials, it has attracted wide attention.

In the early 1970’s, Ford Corporation of the USA developed the earliest SRM drive system, which has a wide range of speed regulation and strong dynamic speed regulation performance. In the early 1980’s, Professor Lawrenson and other researchers introduced their work in the article *Variable Speed SRM* [1]. In this paper, the basic principle and design characteristics of SRM are described, and the control mode and working characteristics of SRM are studied in depth. In 1983, Tasic Drive introduced the first commercial SRM drive system. Following that, other countries have introduced SRM drive system products with useful value.

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Since the 1980s, SRM has been studied in our country. At the same time, there are also a large number of domestic enterprises trying to put SRM drive system into practical application.

As an important research direction of scholars, airborne gravimetry has been studied by a large number of experts and scholars. Gleason and Jekeli first made a lot of simulation studies on airborne gravity vector measurement based on strapdown inertial navigation system [2]. They tried several error separation algorithms, such as windows communication foundation (WCF), gravity field modeling, *etc*. The research shows that the accuracy of horizontal component can reach 7-8 mGal, and that of vertical component is 3 mGal. Senobari [3] used a new error separation algorithm to process the data from the University of Calgary, Canada. The accuracy was slightly improved. The internal coincidence accuracy of the horizontal component of the repeated line was 4-8 mGal. Further, the accuracy could be improved to 2-4 mGal by using WCF method.

At present, the further improvement of the accuracy of vector gravity measurement based on direct measurement depends entirely on the acquisition of high-precision horizontal attitude [4]. Therefore, it is of great theoretical and practical significance to study a new vector gravity measurement method which is less dependent on the accuracy of horizontal attitude to improve the accuracy of vertical deviation and horizontal gravity component. Pulse width modulation (PWM) technology is used to control the driving system of the solid rocket motor. The gravity value of the solid rocket propulsion system is measured by using the attitude error data. The horizontal gravity component estimation model of the solid rocket motor state space is constructed.

Materials and methods

Principle of switched reluctance motor

The SRM is a doubly salient variable reluctance motor. The salient poles of the stator and rotor are all laminated by ordinary silicon steel sheets, and the poles of the stator and rotor cannot be equal. The rotor has neither permanent magnet nor winding, only salient poles, and the stator is winded with concentrated windings. The reluctance of each magnetic circuit changes with the change of the rotor position, so the magnetic field energy of the motor changes with the change of the rotor position, and at the same time the magnetic energy is transformed into mechanical energy. Figure 1 is a schematic diagram of a four-phase 8/6-pole SRM.

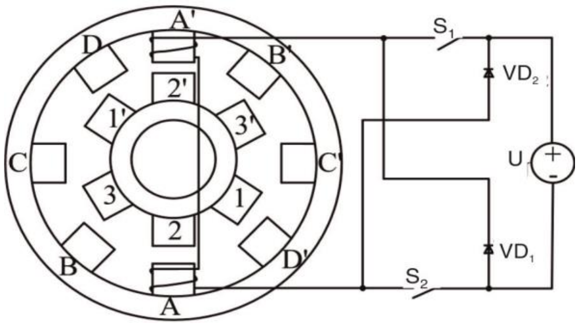

Figure 1. Four-phase 8/6-pole structure SRM structure

According to the law of conservation of energy and electromagnetic induction, the voltage applied to each stator winding end is equal to the sum of resistance voltage drop and induction potential due to flux variation. The instantaneous terminal voltage of each phase of SRM is related to the flux linkage of phase winding resistance as:

$$T = \frac{IL\theta}{2t} \tag{1}$$

where T is the instantaneous terminal voltage of each phase of SRM, I – the torque of group current conduction, L – the amplitude of phase current pulse, θ – the width of phase current pulse, and t – the moment of current conduction of phase winding. Equation (1) shows that the speed control of SRM can be realized by controlling the moment of current conduction of phase winding and the amplitude and width of phase current pulse.

According to the operation characteristics of SRM, it can be divided into three regions: constant torque region, constant power region, and series excitation region [5]. Constant torque region and constant power region are controllable regions for motor operation. By controlling conditions, any actual operation characteristics can be controlled. When the motor runs in the constant torque region, the speed is low and the back electromotive force of the motor is small. Current chopper control is usually adopted. When the motor runs in the constant power region, the rotating electromotive force is larger, the switching element turns on for a shorter time and the current is smaller. When the applied voltage and switching angle are fixed, the torque decreases sharply with the increase of the angular velocity. Because the series excitation characteristic region is uncontrollable, SRM usually does not operate in the series excitation characteristic region.

System driven implementation

The closed-loop control of SRM system is realized by using digital PI regulator of digital signal processor (DSP). The closed-loop operation of all digital speed of SRM system is controlled by the deviation E(t) between the given value and the actual output value. The main function of the control system software is to send out the corresponding winding on and off signals according to the rotor position and actual speed.

The main program block diagram is shown in fig. 2.

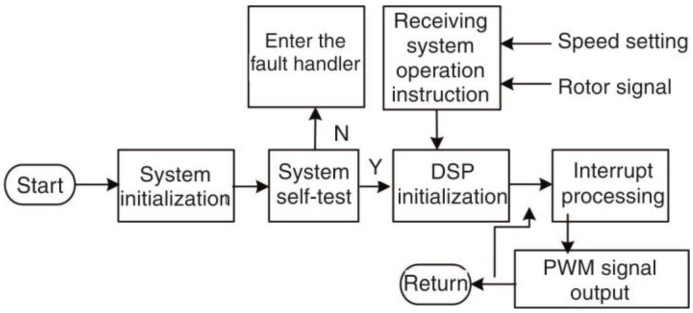

Figure 2. System operation main block diagram

The system software includes a main program and several interrupt service subroutines. The main program initializes the whole system and the operation of the DSP chip. The interrupt subroutines mainly include line sampling, working parameters, fault signal processing, *etc*.

Measurement method of vertical deviation based on attitude error observation

Firstly, the E-N-U co-ordinate system is defined as the navigation co-ordinate system, *i.e*. the n-system. The eastward and northward gravity disturbances are recorded as δg_E (eastward positive direction) and δg_N (northward positive direction), respectively. The north-south and east-west angular components of the vertical deviation are recorded as η and ξ respectively. They are directly related to the horizontal component of the gravity disturbance vector and are defined:

$$\tan\xi = -\frac{\delta g_N}{g} \tag{2}$$

$$\tan\eta = -\frac{\delta g_E}{g} \tag{3}$$

where g is the size of normal gravity. Under the condition of small angle approximation, eqs. (2) and (3) can be approximately written:

$$\xi \approx -\frac{\delta g_N}{g} \tag{4}$$

$$\eta \approx -\frac{\delta g_E}{g} \tag{5}$$

On this basis, the relationship between vertical deviation and attitude error of SRM driving system is analyzed.

Acquisition of attitude reference

In order to obtain the attitude error of solid rocket drive system, it is necessary to provide a high precision ground attitude reference [6]. The error equation of the inertial navigation system in the local geographic co-ordinate system *n* is:

$$\delta\dot{v} = \left[f^n\right]\psi - \left(2\omega_{ie}^n + \omega_{en}^n\right)\delta v - \left(2\delta\omega_{ie}^n + \delta\omega_{en}^n\right)v + \delta g + \nabla^n \tag{6}$$

$$\dot{\psi} \approx -\omega_{in}^n\psi + \delta\omega_{in}^n - \varepsilon^n \tag{7}$$

The position error equation of solid rocket drive system is shown in:

$$\delta\dot{P} = \delta V \tag{8}$$

The solid rocket drive system and zero offset can be modeled by a stochastic constant process:

$$\dot{\nabla}^n = 0 \tag{9}$$

$$\dot{\varepsilon}^n = 0 \tag{10}$$

When the state space vector $X = \{\delta V^T, \psi^T, \delta P^T, [\nabla^b]^T, [\varepsilon^b]^T\}^T$ is selected, the state space model can be given by eqs. (6)-(9). The state space model of solid rocket drive system:

$$\dot{X} = FX + Gw \tag{11}$$

Among them, $w = \{[w_g]^T, [w_a]^T\}^T$ denotes process noise, w_g denotes gyro Gaussian white noise, w_a denotes accelerometer Gaussian white noise, and the formula of noise input matrix is:

$$G = \begin{bmatrix} 0_{3\times3} & C_b^n \\ C_b^n & 0_{3\times3} \\ 0_{9\times3} & 0_{9\times3} \end{bmatrix} \tag{12}$$

Because GPS can provide position and velocity information, the velocity error and position error of solid rocket drive system can be observed directly. Therefore, velocity error and position error are selected as observation variables. When the observation sequence is defined as $z = [\delta V^T, \delta P^T]$ the observation model:

$$z = HX + v \tag{13}$$

Among them,

$$H = \begin{bmatrix} I_{3\times3} & 0_{3\times3} & 0_{3\times3} & 0_{3\times6} \\ 0_{3\times3} & 0_{3\times3} & I_{3\times3} & 0_{3\times6} \end{bmatrix}$$

and v represents the white noise error of GPS velocity and position observation.

The attitude error of the reference attitude is obtained by Kalman filter, and the attitude error of the solid rocket driving system is combined with the attitude error, that is, the required reference attitude angle.

Results

In order to verify the validity of this method in measuring the gravity of solid rocket driving system, the solid rocket driving system based on SRM is simulated on the MATLAB simulation platform. The sampling frequency of original data is 100 Hz, and the sampling frequency of GPS data is 2 Hz [7]. In order to effectively detect the gravity of solid rocket drive system, six measuring points are set up at different positions of solid rocket drive system to detect the gravity in three different directions: north, east, and vertical.

The attitude error estimation results of the solid rocket drive system in the three directions of north, east, and vertical are shown in figs. 3-5.

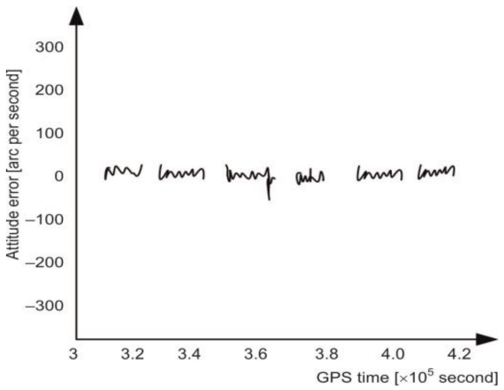

Figure 3. Northbound attitude error estimation results

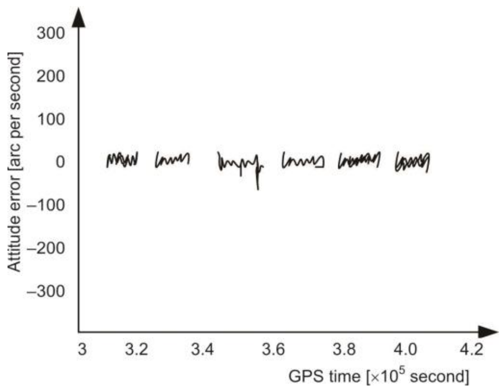

Figure 4. Eastbound attitude error estimation results

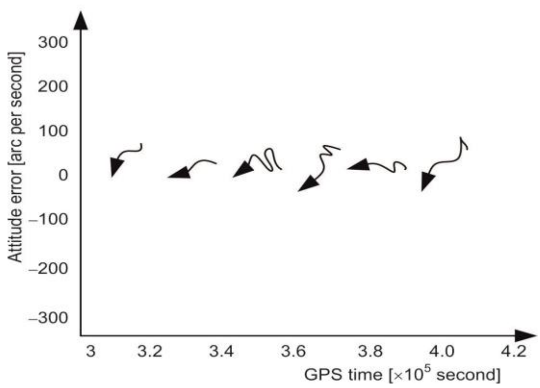

Figure 5. Vertical attitude error estimation results

From the experimental results of figs. 3-5, it can be seen that the attitude errors in the three directions can be estimated effectively by using the proposed method, which provides an effective basis for the accurate gravity measurement of solid rocket drive system.

From the previous experimental results, it can be seen that the horizontal component of gravity disturbance of solid rocket drive system fluctuates near zero in the north, east, and vertical directions in the high frequency part [8]. It can be seen that the high frequency part only reflects the details of gravity information, but does not include deviation and low frequency trend. Therefore, this method is used to measure solid fire. In the gravity process of the rocket drive system, only the low-frequency part of the process noise needs to be removed to obtain accurate measurement results.

The results of gravity measurement at six test points of solid rocket drive system by this method are shown in tab. 1.

Table 1. Gravity test results of the method

Check point	Northward gravity result [mgal]	Eastward gravity result [mgal]	Vertical gravity result [mgal]
Point 1	2.57	2.61	2.66
Point 2	2.91	2.36	2.47
Point 3	2.49	2.08	2.78
Point 4	2.35	3.05	2.48
Point 5	2.19	2.48	2.86
Point 6	3.05	3.58	2.94

From the experimental results in tab. 1, it can be seen that the gravity of solid rocket driving system in different directions can be effectively measured by this method. In order to test the accuracy of gravity measurement of solid rocket drive system, the gravity errors of six test points of solid rocket drive system were measured by this method in the course of statistical simulation experiment, as shown in tab. 2.

Table 2. Gravity test error of the method

Check point	Northward gravity error [%]	Eastward gravity error [%]	Vertical gravity error [%]
Point 1	0.52	0.49	0.38
Point 2	0.65	0.71	0.58
Point 3	0.37	0.61	0.47
Point 4	0.29	0.55	0.63
Point 5	0.78	0.61	0.18
Point 6	0.24	0.17	0.31

Table 2 shows that the gravity error of solid rocket drive system measured by this method is less than 1%. It shows that this method can effectively measure the gravity of solid rocket drive system, and the measurement accuracy is high.

Discussions

New energy vehicle: In recent years, as a green vehicle, electric vehicles have attracted more and more attention. Countries have formulated relevant policies to promote the development and promotion of new energy vehicles. The SRM, as a kind of vehicle driving motor, has good application prospects. At present, most commercial electric vehicles use permanent magnet synchronous motor (PMSM) and asynchronous motor as their driving motors. The PMSM has the advantages of high efficiency and high power density, but its manufacturing process is complex, requiring the use of rare earth permanent magnet materials, and the cost is difficult to control. At present, many scholars and companies have tried to apply SEM in commercial and engineering vehicles, and achieved good results.

Industrial transmission field: In generic industrial transmission field, especially in mining machinery and engineering machinery, the working environment of motor is worse, which requires motor drive system with high mechanical strength, large starting torque, strong overload capacity and good driving performance [9]. The SRM has low starting current, no over current and high starting torque, which is very suitable for driving engineering machinery which needs frequent start-stop or reciprocating motion.

Aerospace field: In aerospace field, motors are required to have strong structure, high reliability and high temperature resistance. General motors cannot be used in high temperature applications either because of their structural limitations or because of their permanent magnet materials. The SRM is very suitable for this occasion because of its non-magnetic material.

The horizontal component of the gravity vector is very sensitive to the attitude of the carrier. In order to obtain the high-precision horizontal component of the gravity vector, it is necessary to ensure high horizontal attitude accuracy. However, the current gyroscope accuracy is difficult to meet this requirement, so it is necessary to estimate and compensate the error of inertial devices, so as to further improve the accuracy of horizontal attitude calculation.

Conclusion

The SRM is very suitable for aerospace applications because of its non-magnetic rotor material. The SRM system with simple structure, firm, non-rare Earth permanent magnet material and high temperature resistance is selected to build the solid rocket driving system. The vertical deviation measurement method based on attitude error observation is used to measure the gravity value of the solid rocket driving system. In order to improve the accuracy of gravity measurement of the solid rocket driving system, the solid fire is used. The attitude and attitude errors of the rocket driving system are combined to obtain high precision ground attitude reference, which provides an effective basis for the successful launch of the rocket. In this paper, the influence of engine fatigue damage on the results is not considered when measuring the gravity of rocket engine. Therefore, the calculation of cumulative damage value of engine will be introduced in the future to further improve the accuracy of gravity measurement.

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