Position control of hybrid stepper motor by model based damping algorithm

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Abstract – The controlling of position of hybrid stepper motor and to improve efficiency, the direct torque control technique is adopted. In this paper a model based damping algorithm for position control of hybrid stepper motor. In general hybrid stepper motors are operated at low-speed conditions. By operating hybrid stepper motors in closed loop operation, it would be replacement of expensive servo motors. For the designing of controller, the electromechanical behavioral model is needed. The model-based damping algorithm for both open-loop and closed-loop controls are proposed. Performance results of the proposed controlling technique are verified by using MATLAB/simulink software.

Index terms - Hybrid stepper motor, damping technique, model-based design, motion control performance.

I. INTRODUCTION

Stepper motors have been found a wide range of applications in machines and devices where robustness, accuracy and small size at a low cost are needed. A large range of stepper motors based on various operation principles have been developed for industrial applications. According to their operation rules, stepper motor can be classified into three types: variable reluctance, permanent magnet and hybrid. The torque in permanent magnet stepper motors is electromagnetic torque produced by the interaction of the stator currents and the rotor flux formed by the magnets. Hybrid stepper motors (HSM) have salient poles on both stator and rotor. One of the most unfavorable features of stepper motor is mechanical resonance, particularly at low speed (typically below 300r/min). Resonance prevents stepper motor to run steadily at certain speeds and reduce the motor’s usable torque. This prevents stepper motor to be used on application that requires smooth low-speed motion. The natural frequency of rotor oscillation about the equilibrium position is

\[ f_n = \frac{1}{2\pi} \sqrt{\frac{T}{J}} \]  

Here

- T – Stiffness of the \( \tau/\omega \) characteristic;
- J - Rotor inertia (kgm\(^2\));
- \( f_n \) - Natural frequency (HZ).

Among various types of stepper motors, HSM are the most commonly used since they have the advantages of higher efficiency and torque capability over the other stepper motors [1]. An open loop position controlled stepper motors are well suitable for applications, but they show a poor performance with respect to very precise motion control and high dynamic requirements. The stepper motor dynamic performance is improved by principle of field orientation, and then it becomes high-dynamic ac-servo [2]. The block diagram of stepper motor investigation is shown in fig.1.

Fig.1. block diagram of stepper motor investigation
The direct torque control (DTC) strategy has been implementing successfully for the controlling of hybrid stepper speed, it has the features of fast response, simple structure and improvement in transient torque response [3]. In general the hybrid stepper motors are controlled by PI, PID controllers, but they are sensitive to parameter variations and load disturbances. Therefore intelligent controllers are using for controlling of HSD drive system, like fuzzy logic, neural network, and genetic algorithms [4]. In this paper, a new torque expression is proposed to model the vibration and resonance of commercial hybrid stepper motor, particularly at low and medium speeds. This is done without using high-order equations and complicated identification procedures. Model-based damping algorithms are proposed for both open-loop and servo modes.

This paper is organized as follows; In Section 2, the proposed dynamic model of HSM is presented. Section 3 describes the proposed open loop damping algorithm. In section 4 the simulation results of model based damping algorithm are described. Finally, in section 5 the conclusion is presented.

II. PROPOSED STEPPER MOTOR MODEL

The simplified stepper model is used most of the time for efficiency. The mathematical model of hybrid stepper motor is mentioned as below equations:

\[ u_a = R_i a + L \frac{di_a}{dt} - wK_m \sin(Ne) \]  \hspace{1cm} (2)

\[ u_b = R_i b + L \frac{di_b}{dt} - wK_m \cos(Ne) \]  \hspace{1cm} (3)

\[ T_e = K_m [(i_b \cos(N\theta) - (i_a \sin(N\theta))] \]  \hspace{1cm} (4)

\[ J \frac{dw}{dt} = T_e - T_L - B_m \omega \]  \hspace{1cm} (5)

\[ N = \frac{360}{2p \theta_s} \]  \hspace{1cm} (6)

Here

- \( R \) is winding phase resistance [\( \Omega \)], \( L \) is winding phase inductance [H], \( K_m \) is torque constant [V.s/rad], \( J \) is total inertial momentum [kgm²], \( B_m \) is friction coefficient [Nms], \( \theta_s \) mechanical step angle in degree, \( p \) is number of phases, \( N \) is no of teeth on the rotor, \( T_e \) is electromagnetic torque [Nm] and \( T_L \) is load torque [Nm].

Fig. 3. Block diagram of the proposed stepper model.

The stepper motor model is controlled by open-loop control technique; the holding current is taken as 2.0 A. The natural frequency is 145 Hz. The resonant speeds are 45, 90, and 178 r/min. They are likely to be caused by detent torque. The first- and second-harmonic detent torque components which excite the resonances, that torque equation is described as:

\[ \tau = K_m [ -i_a \sin(Nr \theta_b) + \]  \hspace{1cm} (7)

\[ -i_b \cos(Nr \theta_b)] - K_d1 \sin(4Nr \theta_b) + \]  \hspace{1cm}

\[ K_d2 \sin(2Nr \theta_b + \phi_2) - K_d1 \sin(Nr \theta_b + \phi_1)] - F_s \]  \hspace{1cm}

Here

- \( K_d1 \) Amplitude of the first-harmonic torque ripple (Nm);
- \( \phi_1 \) Phase shift of the first-harmonic torque ripple (rad);
- \( K_d2 \) Amplitude of the second-harmonic torque ripple (Nm);
- \( \phi_2 \) Phase shift of the second-harmonic torque ripple (rad);
- \( F_s \) Static friction (Nm).
Let us assume that, there is no load is applied on motor. The load is expressed as:

$$\begin{bmatrix} \theta' \\ \omega' \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} \theta \\ \omega \end{bmatrix} + \begin{bmatrix} 0 \\ -\frac{D}{J} \end{bmatrix} \begin{bmatrix} \omega \\ T \end{bmatrix}$$  \hspace{1cm} (8)

Here D is damping factor is taken as 0.001 N.m/rad.s\(^{-1}\) for lightly damped system.

The stepper motor model is shown in figure.3. The model is represented with electric dynamics, torque expression, and simple inertia load. Simulation frequency needs to be at least 100 KHz for voltage-mode electrical model to get result. The block diagram of servo stepper motor system is shown in fig.4.

![Block diagram of the servo stepper motor system.](image)

Current control is done by PI current loop. \(K_p\) and \(K_i\) are proportional gain and integration gain of current loop, respectively, the current and voltage commands in d-q reference frame are represented as below [5]:

$$i_{d,cmd} = 0$$  \hspace{1cm} (9)

$$i_{q,cmd} = \frac{1}{K_m} \left[ K_{d4} \sin(4N_r\theta_{fb}) + K_{d2} \sin(2N_r\theta_{fb} + \phi_2) + K_{d1} \sin(N_r\phi_{fb} + \phi_1) + F_s \right]$$  \hspace{1cm} (10)

$$v_d = K_p \left( i_{d,cmd} - i_{d,fb} \right) + K_i \int (i_{d,cmd} - i_{d,fb}) dt$$  \hspace{1cm} (11)

$$v_q = K_p \left( i_{q,cmd} - i_{q,fb} \right) + K_i \int (i_{q,cmd} - i_{q,fb}) dt$$  \hspace{1cm} (12)

By using d-q or park transformation the motor phase currents \(i_a, i_b\) are transformed to \(i_d, i_q\). They are represented as:

$$\begin{bmatrix} i_{d,fb} \\ i_{q,fb} \end{bmatrix} = \begin{bmatrix} \cos(N_r\theta_{fb}) & \sin(N_r\theta_{fb}) \\ -\sin(N_r\theta_{fb}) & \cos(N_r\theta_{fb}) \end{bmatrix} \begin{bmatrix} i_{a,fb} \\ i_{b,fb} \end{bmatrix}$$  \hspace{1cm} (13)

The results of the identification are \(K_{d4} = 0.006, K_{d2} = 0.014, K_{d1} = 0.011, \phi_2 = \pi, \phi_1 = \pi/2, F_s = 0.029 \) (during clockwise motion), and \(F_s = -0.029 \) (during anticlockwise motion). The unit of all constant K’s is Newton meters.

**III. OPEN LOOP DAMPING ALGORITHM**

The open-loop control damping algorithm is executed by eliminating resonances. The d-q references frame current commands are represented as follows:

$$i_{d,cmd} = 2.0$$  \hspace{1cm} (14)

$$i_{q,cmd} =$$

$$\frac{1}{K_m} \left[ K_{d4} \sin(4N_r\theta_{fb}) + K_{d2} \sin(2N_r\theta_{fb} + \phi_2) + K_{d1} \sin(N_r\phi_{fb} + \phi_1) \right]$$  \hspace{1cm} (15)

Position feedback \(\theta_{fb}\) replaced by position command \(\theta_{cmd}\) for d-q transformation in equation
(13). The three-phase space-vector PWM (SVPWM) technique is represented as [6]:

\[
\begin{bmatrix}
v_a \\ v_b \\ v_c 
\end{bmatrix} =
\begin{bmatrix}
1 & 0 & 1 \\ 0 & 1 & 1 \\ 0 & 0 & 1
\end{bmatrix}
\begin{bmatrix}
v_a \\ v_b \\ v_c 
\end{bmatrix}
\]  

- (16)

\[v_{\text{max}} = \max\{v_a, v_b, 0\}\]  

- (17)

\[v_{\text{min}} = \min\{v_a, v_b, 0\}\]  

- (18)

\[v_0 = \frac{v_1}{2} - \frac{(v_{\text{max}} + v_{\text{min}})}{2}\]  

- (19)

Here \(v_z\) is the bus voltage supply of the SVPWM chopper.

The zero-order hold is applied on \(v_a, v_b, v_c\) to simulate characteristic of periodic PWM of chopper drive. The open-loop stepper motor drive system block diagram is shown in fig.5. And model for proposed servo controller is shown in figure.6.

![Fig.5. block diagram of open-loop stepper motor system](image)

![Fig.6. Model for proposed servo controller.](image)

IV. SIMULATION RESULTS

A hybrid stepper motor of full step size 2.0° is taken for the design in MATLAB model. It is having coil resistance 1.2 Ω, winding inductance 2.5 mH, rotor inertia of 50*10^-6 kg.m², rated current of 3 A, holding torque of 1.35 N*m, and force constant \((Km)\) of 0.3 N*m/A.

In all simulations, the command is a speed ramp from 0 r/min at \(t = 0\) s to 200 r/min at \(t = 0.8\) s. In the first case, no damping is applied, so \(i_{q,\text{cmd}} = 0\).

Three resonant speeds are observed at about 45, 80, and 170 r/min which match with 43, 86, and 173 r/min observed in the experiment, respectively. Simulation result, velocity feedback, and error of the open-loop system without damping are shown in fig.7. By injection of fourth harmonic torque compensation, first resonance is damped is shown in fig.8.
The injection of the first- and second-harmonic torque compensations can damp out the second and third resonances, these are shown in fig.9, fig.10, respectively. The simulation results of the injection of all three harmonic torque compensations in \( i_{q\text{-cmd}} \) are shown in fig.11. At the low-speed ranges almost the voltage ripple is eliminated.

![Fig.7. Simulation result, velocity feedback, and error of the open-loop system without damping.](image1)

![Fig.8. Simulation result: removal of the first resonance by the injection of the fourth-harmonic torque compensation.](image2)

![Fig.9. Simulation result: removal of the second resonance by the injection of the second-harmonic torque compensation.](image3)

![Fig.10. Simulation result: removal of the third resonance by the injection of the first-harmonic torque compensation.](image4)
Fig. 11. Simulation result: removal of all three resonances by the injection of the first-, second-, and fourth-harmonic torque compensations.

The system is first set to run without damping. It is then tested with the injection of the fourth-, second-, and first harmonic torque compensations to damp out the first, second, and third resonances, respectively. Finally, it is tested with the injection of all the three harmonic torque compensations. The corresponding waveforms for above description are shown in fig.12, 13.

Fig. 12. Experimental result: velocity feedback without damping.

Fig. 13. Experimental result: removal of all three resonances by the injection of the first-, second-, and fourth-harmonic torque compensations.

CONCLUSION

The model based damping technique for hybrid stepper motor is successfully done with efficiently. Compensation of low-order torque ripple is proven to be effective to remove vibration and resonance. The damping algorithm for both open-loop and servo modes is applied and verified very efficiently by simulation results. The new torque expression is proposed in this paper for commercial hybrid stepper motor. Park (d-q) transformation (ab -dq) is used for generation of feed-back current commands. The digital PI current loop is designed for inverse park transformation (dq -ab). Successfully compensated the first-, second-, and fourth-harmonic torque ripples by the proposed damping technique. The verification of performance characteristics of model-based damping technique is done by MATLAB/simulink software. And simulation results are described in section-IV. The future scope of the proposed damping algorithm is “the studying of parameter sensitivity”.

Fig. 14. Simulation result: removal of all three resonances by the injection of the first-, second-, and fourth-harmonic torque compensations.
REFERENCES


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