MODELING WITH CURRENT DYNAMICS AND VIBRATION CONTROL OF TWO PHASE HYBRID STEPPING MOTOR IN INTERMITTENT DRIVE

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Abstract: This paper presents modeling of stepping motor and control design of input pulse timing for the suppression control of vibration. The stepping motor has the transient response of electric current for the pulse input. Therefore, the motor model considering the transient response of the current is built. The validity of the proposed model is verified by comparing the model considering the transient response of the current with the one without its consideration. Design of the pulse input timing in the method of the four pulse drive is realized to achieve the desired angle without vibration and overshoot using an optimization method. Finally, the effectiveness of the proposed method is demonstrated by comparing simulation results with experiments.

1 INTRODUCTION

The stepping motor has been widely used for factory automation (FA) and office automation (OA) equipment, because it is able to realize high-accuracy positioning by an open loop control. It is used also for the production process of electronic parts, and then the settling time of the stepping motor is directly linked to the productivity. Therefore, the high speed and the low vibration are strongly desired in the production line. However, the stepping motor vibrates around the neighborhood of the equilibrium points owing to the step-wise drive from the viewpoints of the motor characteristics. To dampen the vibration of motor, (i) micro step drive method that makes changes the exciting current change in details, and (ii) a inverse phase excitation dumping, and (iii) a delay damping method, are proposed(D.Ebihara and T.Iwasa, 1984). Especially, the micro step drive is possible to drive with the low vibration. Because it is made to drive by changing at smaller angle than the basic step angle by making the exciting current change in details (D.Ebihara and T.Iwasa, 1984)D It is necessary to give the excitation instruction considering the dynamic characteristic of the system in the transient state of the start and the stop times. As an adjustment method of the excitation sequence, the method of applying a lowpass filter as a pre-compensator (T.Miura et al., 2000), and the method that uses the genetic algorithm (T.Miura and T.Taniguchi, 1999) are proposed. The vibration control considering robustness for the vibration of the inertia load is studied by these methods. Moreover, the technique for decreasing the resonance using the position and the speed feedback estimated by the observer is given (S.M.Yang and E.L.Kuo, 2003).

The stepping motor has a strong nonlinearity. Therefore, when the linear control theory is applied, it is often linearized around the equilibrium point. However, the operation area of the stepping motor is wide, so variable control gain is necessary to keep an excellent control performance. Whereas, the method using an exact linearization by means of nonlinear feedback and coordinate transformation of state space is proposed (M.Bodson et al., 1993). Moreover, the application of the control algorithm of the artificial intelligence system such as fuzzy theory (F.Betin and D.Pinchon, 1998) and neural network (K.Laid et al., 2001) are provided.

Those control methods are mostly discussed concerning with a step drive and a continuous drive. However, the high speed and the high accurate positioning system by the fine drive might be requested in the FA equipment. In this case, the positioning by a few number of pulse order is performed.

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Therefore, in this paper, the vibration suppression is studied when the stepping motor is intermittently driven by a predetermined few number of step, assuming FA application. The response of the stepping motor is varied by the influence of transient response of the current, when the command pulse interval is rather short for the excitation phase. Therefore, a mathematical model comprised of the torque equation with the dynamics of the current in the generated torque is presented. By means of the phase plane analysis and the optimization for the obtained mathematical model, the pulse control timing with a low vibration is obtained. The validity of the proposed model is confirmed through the experiments and the simulations.

2 EXPERIMENTAL SETUP

The experimental setup consists of motor with the inertia load connected with a solid shaft as shown in Figure 1. The shaft has been extended from both ends of the motor, and the inertia load is installed in a one end. The encoder has been installed to the shaft on the other side.

The block diagram of the driving system of a stepping motor is shown in Figure 2. The motor driver uses the commercial item, and the motor is driven up to the fixed current drive in a full step. The pulse input is carried out by the designed timing in advance by numeric calculation. The pulse is outputted according to the timing specified from the Pulse Oscillator. The excitation current is passed by excitation phases by the motor driver, and the motor is driven. The excitation phase of the motor can be switched by the pulse being input from Pulse Oscillator to Motor Driver. In this study, the motor is used with the excitation phase comprised of Phase A, Phase B, Phase $\bar{A}$, and Phase $\bar{B}$. The excitation phase switches in order of $AB \to B\bar{A} \to \bar{A}\bar{B} \to \bar{B}A \to AB$ by two phase excitation. The rotor angle is detected by the encoder of accuracy of 36000[pulse/rev]. The encoder signal is doubled by up-down counter of four.

3 STEPPING MOTOR MODEL

3.1 Modeling of Stepping Motor

The stepping motor rotates stepwise by switching the excitation phase by input pulse. Therefore, Eq.(1) can be derived from the equation of motion of rotation system (D.Ebihara and T.Iwasa, 1984).

$$J\ddot{\theta} + D\dot{\theta} + T_L = T_M \tag{1}$$

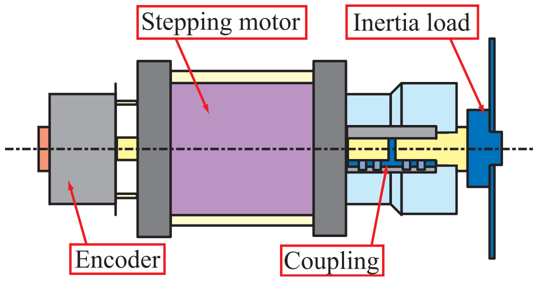

Figure 1: Construction of stepping motor.

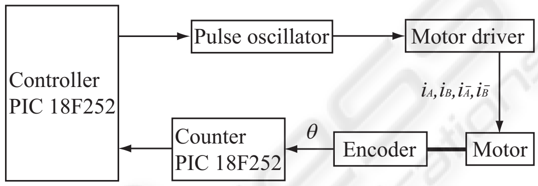

Figure 2: Block diagram of driving system for a stepping motor.

,where J is an inertia moment, D is a damping coefficient, T_L is a load torque, T_M is the generated torque of motor and θ shows a rotor angle. The generated torque can be described as the sum of the generated torque of each phase. The generated torque of each phase of two phase hybrid stepping motor is represented by the following equations.

$$T_A = -i_A K \sin(N_R\theta) \tag{2}$$

$$T_B = -i_B K \sin(N_R\theta - \frac{\pi}{2}) \tag{3}$$

$$T_{\bar{A}} = -i_{\bar{A}} K \sin(N_R\theta - \pi) \tag{4}$$

$$T_{\bar{B}} = -i_{\bar{B}} K \sin(N_R\theta - \frac{3\pi}{2}) \tag{5}$$

,where K is a torque constant, N_R is the number of a rotor teeth and, i_A, i_B, $i_{\bar{A}}$ and $i_{\bar{B}}$ are excitation current of each phase. The suffix of torque T and current i shows phase A, B, $\bar{A}$ and $\bar{B}$ respectively. Whenever the pulse is input in the two phase stepping motor, it is excited in order of $AB \to B\bar{A} \to \bar{A}\bar{B} \to \bar{B}A \to AB$. Moreover, because $i_A = -i_{\bar{A}}$ and $i_B = -i_{\bar{B}}$, then it follows that $T_A = T_{\bar{A}}$ and $T_B = T_{\bar{B}}$. Therefore the generated torque T_M becomes the sum of T_A and T_B. If a magnetic axis is defined as $\theta = 0$ when phase A and phase B are the excited states, the generated torque is shown as follows.

$$T_M = -i_A K \sin(N_R\theta + \frac{\pi}{4}) - i_B K \sin(N_R\theta - \frac{\pi}{4}) \tag{6}$$

Generally, it becomes $i_A = i_B = i$ at the fixed current drive. And Eq.(7) is derived by the trigonometric function formula.

$$T_M = -\sqrt{2} i K \sin(N_R \theta) \tag{7}$$

This formulation is explained by the reference of D.Ebihara and T.Iwasa, 1984. However, there is a transient state between the time of the pulse input and the switching time of the current of the excitation phase, as shown in Figure 3. Here, Figure 3 shows the excitation current transition of each phase after pulse input when the stepping motor is driven, and Exp I_A is a current of phase A and $\overline{A}$, Exp I_B is a excitation current of phase B and $\overline{B}$, Sim I_A and Sim I_B is the assumed current in simulation. From Figure 3, when the first pulse is input, the Exp I_A is switched from the plus into the minus. It is meant to change the phase $\overline{A}$ from the phase A, because Exp I_A is the excitation current of phase A. Here, the change of the current in Exp I_A is almost linearly changed from the value of $+1.2$[A] to the value of -1.2[A], when the excitation phase is switched. Excitation current Exp I_B of the phase B is also similar. Therefore, the excitation current is thought that the current is changed almost linearly from the input of the pulse up to the switching the excitation phase as shown in Sim I_A and Sim I_B. The current response of interval T_d[s] is shown in Eq.8, when the elapsed time after inputting the pulse is defined as T_i[s], and the time from the input of the pulse up to switching the excitation current is defined as T_d[s].

$$i_{A,B} = -(1 - 2\frac{T_i}{T_d})I, \qquad (0 \le T_i \le T_d) \tag{8}$$

,where I is the rated current of the motor. From Eq.(1), Eq.(6) and Eq.(8), the equation of motion is shown in Eq.(9).

$$J\ddot{\theta} + D\dot{\theta} + T_L = -i_A K \sin(N_R\theta + \frac{\pi}{4}) - i_B K \sin(N_R\theta - \frac{\pi}{4}) \tag{9}$$

,where i_A is shown by the following equation. As for i_B, it is omitted in this paper, due to the limitation of paper, because it is similar equation.

$$i_A = \begin{cases} I, & (Phase\ A) \\ -(1-2\frac{T_i}{T_d})I, & (Phase\ A \rightarrow Phase\ \overline{A}) \\ -I, & (Phase\ \overline{A}) \\ (1-2\frac{T_i}{T_d})I, & (Phase\ \overline{A} \rightarrow Phase\ A) \end{cases} \tag{10}$$

3.2 Parameter Identification

The parameter of Eq.(9) is identified from the step response of stepping motor. The parameter is decided to be minimized the error sum of square by a Simplex Method(M.Hamaguchi et al., 1994). Here, J, D and T_L are the parameters including the encoder. The step response result is shown in Figure 4. The response corresponds with the experiments and the simulations, and then the identification is appropriate, because simulation agrees well with experimental results. The model parameter is shown in Table 1, where α is a step angle.

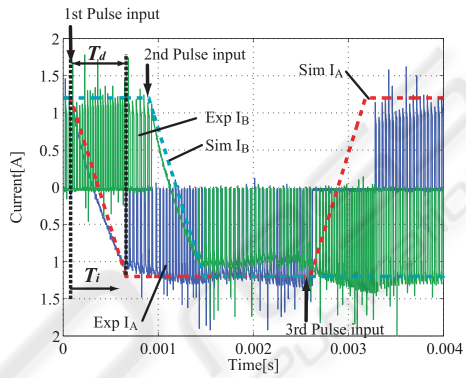

Figure 3: Current response of stepping motor.

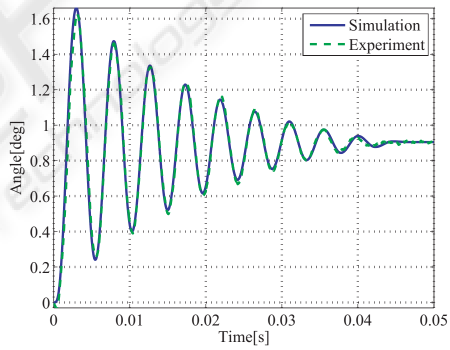

Figure 4: Step response of proposed model.

Table 1: Motor parameters.

Parameter	Value
α	0.9 [deg]
I	1.2 [A/phase]
J	164.94×10^{-7} [kg·m^2]
D	0.001442 [kg·m·s]
T_L	0.00357 [N·m]
K	0.2662 [N·m/A]
T_d	0.0007 [s]

3.3 Comparison Between Proposed and Conventional Model

The conventional model is written by the following equation using Eq.(1) and Eq.(7).

$$J\ddot{\theta}+D\dot{\theta}+T_L=-\sqrt{2}IK\sin(N_R\theta) \qquad (11)$$

The model parameters which did not consider the current response can be also identified from the step response in the same way with subsection 3.2. The parameters obtained from the optimization are shown in Table 2. The result of the step response is shown in Figure 5. Experiments and simulations are almost well in agreement as shown in Figure 5

The model which did not consider the current response is shown in Eq.(11), and the proposed model are compared. In comparison, the response of motor in experiment and simulation are checked, when four times pulses are inputted to motor. T_1[s] is the interval of input pulse from the first pulse to the second pulse. And T_2[s] is the interval of input pulse from the second pulse to the third pulse, T_3[s] is the interval of input pulse from the third pulse to the fourth pulse, and then T_1=400[μs]CT_2=2331[μs]CT_3=1428[μs]. The pulse timing of T_1, T_2, and T_3 is respectively obtained by using Simplex Method to minimize the evaluation function as shown in Eq.(12) at Section 4. Experiment and simulation results are shown in Figure 6.

The rising time of the conventional model is shorter than proposed model, and the residual vibration remains close to the desired value. However, simulation result of the proposed model agrees well with the experimental result. As a result, we confirmed that the more highly accurate model can be obtained by the proposed model considering the current response.

Table 2: Parameters of conventional model.

Parameter	Value
J	168.56×10^{-7} [kg·m^2]
D	0.001505 [kg·m·s]
T_L	0.001902 [N·m]
K	0.2582 [N·m/A]

4 DESIGN OF PULSE INPUT TIMING

In this paper, the time that the rotor reaches the desired angle without vibration, when input using four pulses are given to the stepping motor, is determined based on the proposed model. The time of the first input pulse is 0[s]. The one step angle is $\alpha = 0.9$[deg], so the desired angle by four input pulse is 3.6[deg]. The pulse interval T_1, T_2, and T_3 denotes the same meaning with the preceding section. When T_1 are changed from 300[μs] up to 2200[μs] every 50[μs] interval, total 39 patterns, optimal T_2 and T_3 are decided

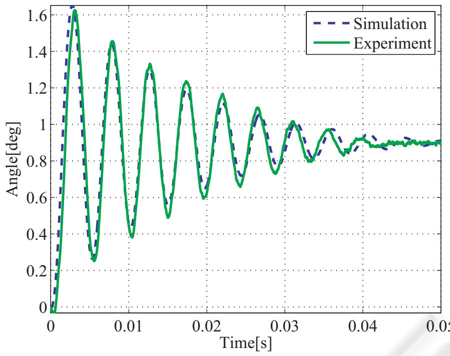

Figure 5: Step response of conventional model.

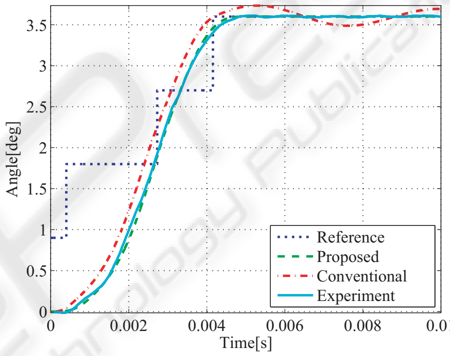

Figure 6: Comparison result of the conventional and proposed model.

in the same way. The optimization problem of minimizing the following evaluation function is solved as a decision method.

$$\min_{T_2,T_3} J_c=(\max\theta(t)-4\alpha)^2, \quad (T_1+T_2+T_3+T_d\le t) \qquad (12)$$

,where T_d is the settling time of the current for the pulse input. To minimize the overshoot at the desired angle, a Simplex Method is used as an optimization technique. The evaluation function is decided to be the error square of the desired angle and the maximum angle after reaching at around the neighborhood of the desired angle. If the overshoot with the desired angle is small, the vibration then is also a little, because the stepping motor is settled at the desired angle decided according to the excitation phase.

The overshoot of the angle in the control time obtained by a Simplex Method were almost 0.0009[deg] or less. The overshoot was less than 0.1 % against the step angle of $\alpha = 0.9$[deg] by a Simplex Method. Therefore, it is thought that there is little overshoot.

Simulation results using control timing obtained in a Simplex Method stated above are shown in Figure 7 and Figure 8. Here, Figure 7 shows the time response of rotor angle and angular velocity, and Figure 8 shows the phase plane trajectory. The point in the figure is control time of the pulse input, and the arrows shows transitions of the pulse input timing when T_1 changes from 300[μs] to 2200[μs]. *VelocityErrorPlane* method is commonly used in the phase plane trajectory of the stepping motor to prevent a transverse axis from becoming long (D.Ebihara and T.Iwasa, 1984). Here, in *VelocityErrorPlane* method, the phase difference $\frac{\pi}{2}$ is subtracted whenever the excitation phase is switched. However, in this paper, to see the response to control time of pulse four times, the angle without subtracting the phase difference was drawn in a transverse axis.

There is a width of about 1[ms] to settling to the desired angle using pulse timing in this study. Motion time can be shortened to use the pulse timing in the trajectory with large angular velocity on the phase plane.

When the current dynamics is not considered, the changeover point on the phase plane without vibration by the desired angle is 3.6[deg] and 0[deg/s] (D.Ebihara and T.Iwasa, 1984). However, it is confirmed that the last changeover point is the smaller angle than 3.6 [deg], when there is the transient response of the current. As seen from Figure 7, the time to reach at the desired angle is about 700 [μs] after the fourth input pulse is given, and it corresponds to the transient response of the current for pulse input assumed from Figure3. Consequently, it is confirmed that the excitation sequence with a little vibration can be obtained only by considering the response of the current. Therefore, to realize the vibration-free response in the full step drive, the proposed model considering the current dynamics and the control design based on the model are made clear through these analyses.

5 EXPERIMENTAL RESULTS

Three patterns are selected based on the timing designed in Section 4 and experiments are done. The pulse control time used in the experiments is shown in Table 3. Experimental results of No.1, No.2, and No.3 are shown in Figure 9, Figure 10, and Figure 11, respectively.

Simulation results of both the angles and the angular velocity corresponds well to experimental results. Especially, the vibration of experimental number No.1 was suppressed within 0.01 [deg] as the same as resolution of encoder.

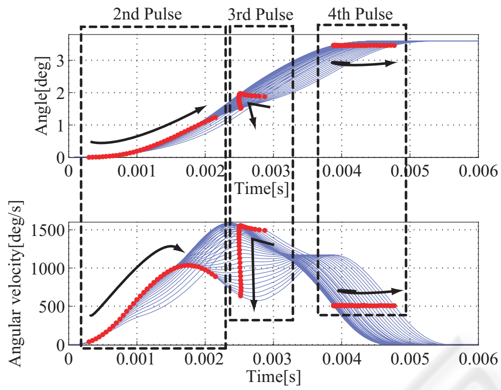

Figure 7: Simulation result of time response using 4 pulse input of various control time.

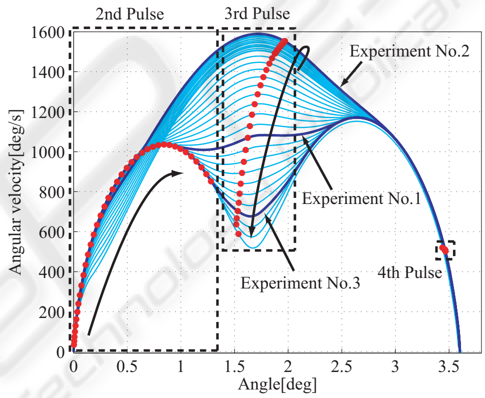

Figure 8: Phase plane trajectory of stepping motor.

Moreover, a vibration of about 810[Hz] is confirmed that is higher than eigenfrequency of the motor in Figure 10 and Figure 11. To realize more highly accurate vibration suppression, it is necessary to consider the vibration in the present model. It is thought that this higher harmonic vibration is due to the influence of the harmonic component of the current, the magnetic field of the drive circuit and the stepping motor.

Through these results, the proposed model considering the response of the current enabled us to achieve the pulse control with little vibration.

Table 3: Pulse timing.

Experiment No.	T_1[μs]	T_2[μs]	T_3[μs]	Total[μs]
No.1	1700	810	1810	4320
No.2	800	1722	1368	3890
No.3	2050	476	2144	4670

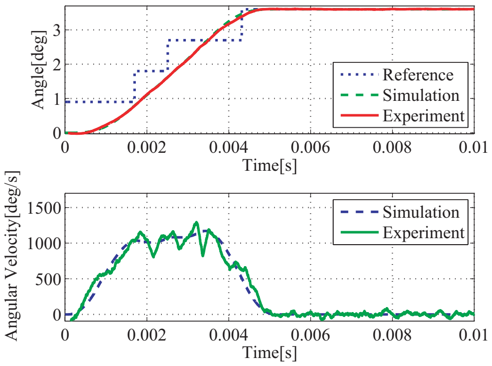

Figure 9: Experimental result of case No.1.

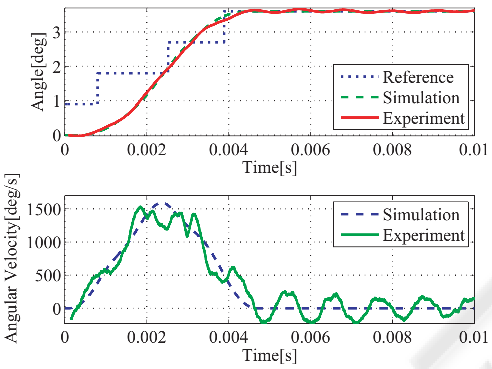

Figure 10: Experimental result of case No.2.

6 CONCLUSIONS

In this paper, a mathematical model by means of the torque equation of the stepping motor considering the dynamics of the current has been built. The relation between the response of the current and the excitation timing on the phase plane were discussed for a full step drive of four pulses. From the simulation, in the system that there is the transient response in the current, it was confirmed that the input timing of the last pulse should be conducted before the end time, considering the duration time of current delay. The validity of the proposed model was shown by the comparison between the simulation and the experiment. The pulse input timing without vibration was decided by means of four pulses, and excellent vibration control was able to be realized based on the proposed model using Simplex Method. The effectiveness of the proposed approach was demonstrated through experiments and simulations.

Robustness to the higher harmonic vibration and

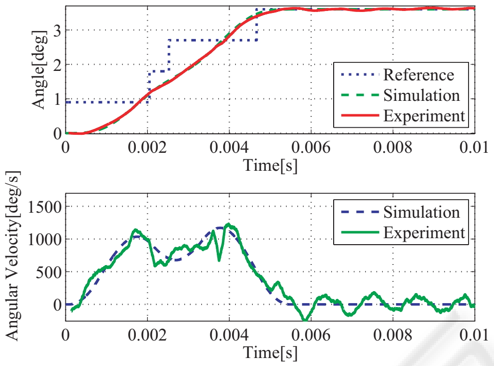

Figure 11: Experimental result of case No.3.

model parameter variation by load variation, etc should be investigated, and then robust control must be achieved in near future.

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