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ANALYSIS OF DRIVING TORQUE OF FEED DRIVE SYSTEM DURING MICROSCOPIC MOTION

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Abstract: This paper provides more details of dynamic behaviors of the feed drive system which consists of an AC servo motor and rolling elements etc. In the feed drive system, the nonlinear behaviors of the internal structure of the rolling element have an crucial influences on precise control performance. Our special interest is how to verify the fundamental data of dynamic behaviors of the feed drive system in the vicinity of a microscopic displacement. Experimental data show that the driving torque curve becomes distorted as the input amplitude of sinusoidal wave to the system gets larger, but the curve forms are independent of the input frequencies.

Key words: driving torque, feed drive system, microscopic motion

1. INTRODUCTION

High accurate control performance of feed drive systems meet the requirements for machining industries through all ages. Today, the required accuracy has reached a nanometer level. To achieve the control performance with the accuracy of tens nanometers level and the stroke of tens millimeters one, the complex servo system combining a coarse table with a fine table has been proposed in previous papers. In this system, the coarse table consists of a AC servo motor, a ball-screw and linear ball guide ways, and the fine table driven by a piezo-actuator mounted on the coarse table. However, since the structure of this system is extremely complex due to having two mechanisms, the size of the device become significantly larger and it is difficult to control the total system successfully.

The reason for the combination of the coarse motion and the fine motion is that the resolution of the coarse motion can only be obtained by about 1μm due to the effects of the nonlinear behaviors of the rolling elements with the coarse motion. But, the analysis on the static behaviors, that is the relation of the displacement and the force for the rolling elements has already been given. The resolutions of the rotary encoder necessary for controlling the AC servo motor and those of the linear scale for measuring the position of the table have been improved significantly. Therefore, if the dynamic behaviors of rolling elements were modeled mathematically and the control system considering the dynamic characteristics was designed, the feed drive system with the accuracy of tens nanometers level and the stroke of tens millimeters one would be achieved by only one mechanism without the fine table.

In the long history of the feed drive systems, though the analysis of static behavior has been done, the dynamic behavior is not so examined. And the analyzed characteristics have been analyzed for the entire feed drive mechanism with the rolling elements. In this study we observe the nonlinear behaviors of the feed drive system and investigate which element influences the motion accuracy of the feed drive system greatly. Concretely, the analysis of the dynamic driving torque when the sinusoidal wave input of microscopic displacement was applied to the AC servo motor and the detail analysis have been done. These results will contribute to mathematical modeling to illustrate the nonlinear behavior of the feed system with the rolling elements.

This paper consists of several sections: Modeling experimental apparatus is presented in Section 2. Measurement results of driving torques and the discussions are presented in Section 3, and the conclusions are summarized in Section 4.

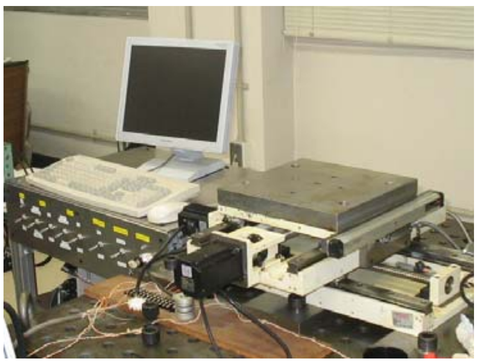


Fig. 1. Experimental apparatus

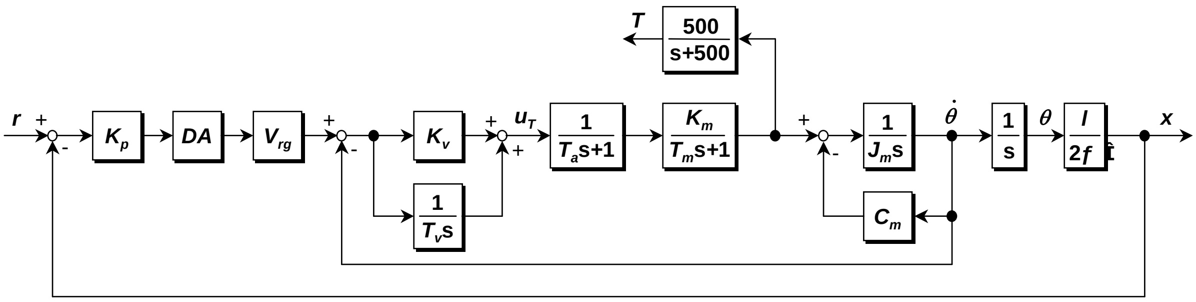


Fig. 2. Block diagram of feed drive system for microscopic motion

Table 1 Parameters of model

Symbol	Unit	Value	Symbol	Unit	Value
K_p	1/m	500	T_a	s	1.0×10^{-3}
DA	V	10	T_m	s	6.9×10^{-4}
V_{rg}	rad/(sV)	52.4	K_m	–	1.0
K_{vp}	1/s	40	C_m	Nms/rad	1.0×10^{-4}
K_v	Nms/rad	2.92×10^{-3}	J_m	kgm^2	1.16×10^{-5}
T_{vi}	s	0.02	l	m	0.005
T_v	s	5.84×10^{-5}			

2. EXPERIMENTAL APPARATUS AND MODELING

2.1. Experimental Apparatus

The overall view of the experimental apparatus is shown in Fig. 1. Our controlled object is an XY table system using many machine tools. This system consists of two feed drive systems (corresponding to each of the X and Y axes). Either one of feed drive systems includes an AC servo motor and an amplifier, a ball screw and a table supported by linear ball guides. The AC servo motor and the ball screw are connected by a coupling. Also, The feed drive system contains some rolling elements, the bearing for the AC servo motor, the ball screw, the bearing that supports the ball screw and the linear ball guide. The nonlinear behaviors of the rolling element cause the degeneracy of motion accuracy of the feed drive system in microscopic motion [1]. Since there are some rolling elements in the feed drive system, we cannot indicate which element has strong influence on the motion accuracy. So, we focus on the dynamic behaviors of AC servo motor only.

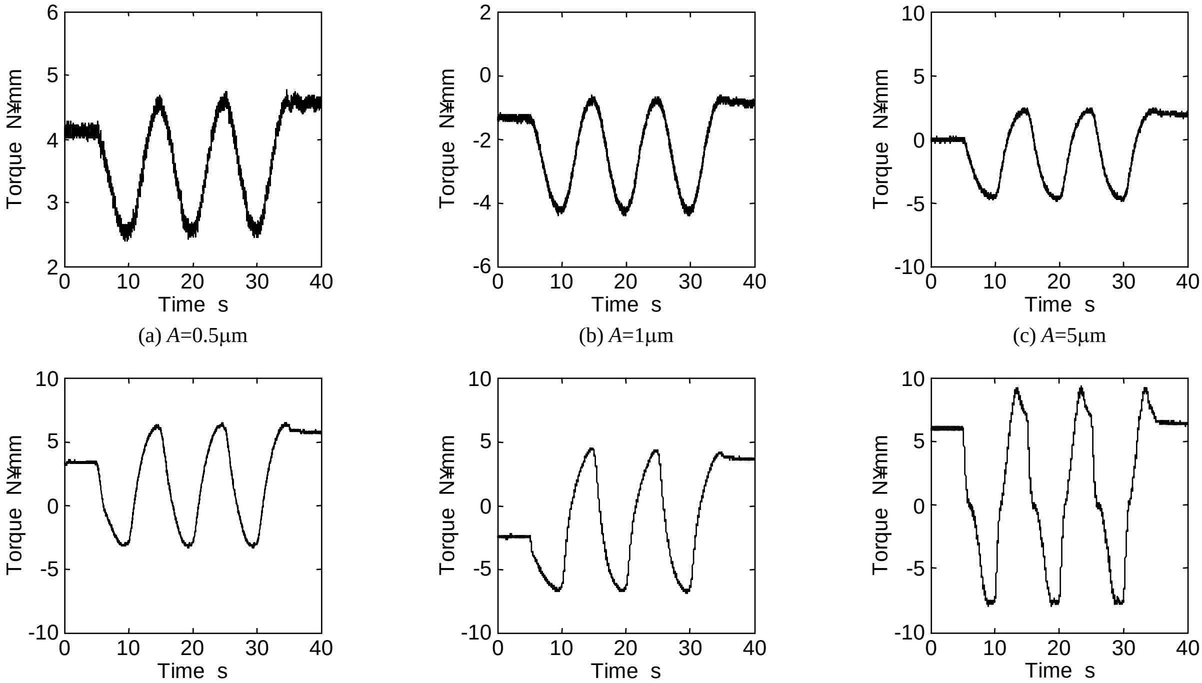
In this study, we examine only the characteristics of the AC servo motor controlled by a full closed feedback loop. In general the feedback signal is the rotational angle from a rotary encoder installed in the AC servo motor. But, it is convenient for us to define the linear displacement to express the dynamic behaviors of feed drive system in microscopic motion. We adopt the feedback signal converted from the rotational angle to the linear displacement. In our experiments apparatus the lead of ball screw is 5mm and the output of rotary encoder is 17 bits, so that 131,072 pulses are equivalent to one rotation. Consequently, the one pulse of the rotary encoder corresponds to the linear displacement of 38nm.

The electric current and the output velocity of the AC servo motor can be successfully controlled by a servo amplifier. That is, the servo amplifier has the inner control loop. The rotary encoder acquires the displacement signal of the table and sends it to the control unit (the DSP board included in the PC). In this way, the feed drive system makes it possible to control the output displacement of the table as the controlled variable. The driving torque applied to the AC servo motor can be measured with an analog monitoring function installed in the servo amplifier. Through an analog monitoring terminal, the electric voltage signal can be measured as the driving torque, in which the rated torque of the motor corresponds to the electric voltage of one volt. Since the voltage signals are introduced into the DSP board through AD converters, all data can be easily recorded simultaneously.

In our experiments, it should be noted that the effects of the measurement noise on the driving torque can be reduced by a relaxation filter as shown in Fig. 2. The feed drive system can be operated at the control sampling period of 0.1ms, and all data can be recorded at the sampling period of 1ms after the system is triggered off the reference input.

2.2. Modeling

The control system of the AC servo motor is shown in Fig. 2, where r (mm) is the input displacement, u_T (Nm) is the output torque of the velocity loop, T (Nm) is the driving torque and the measured value of T can be finally obtained



(a) A=0.5μm (b) A=1μm (c) A=5μm
(d) A=10μm (e) A=20μm (f) A=100μm

Fig. 3. Driving torques for various input displacements

th
rad/s. $\dot{\theta}$ (rad/s) is the rotational velocity, θ (rad) is the rotational angle and x (mm) is the output displacement. K_p (1/m) is the displacement gain, DA (V) is the DA convertor ratio. V_{rg} (rad/sV) is the velocity reference gain, K_{vp} (1/s) is the velocity loop gain, K_v (Nms/rad) is the velocity gain, the relationship of the K_{vp} to K_v is K_v=$J_m K_{vp}$, Tvi (s) is the integral time of the velocity loop, T_v (s) is the integral time, the relationship of the T_{vi} to T_v is T_v=$K_v T_{vi}$, T_a (s) is the time constant of a torque filter. T_m (s) is the time constant of an approximated current feedback loop, K_m (–) is the gain of an approximated current feedback loop. J_m (kgm^2) is the inertia of motor rotor. C_m (Nms/rad) is the viscous damping coefficient of the motor bearings and l (m) is the lead of the ball screw.

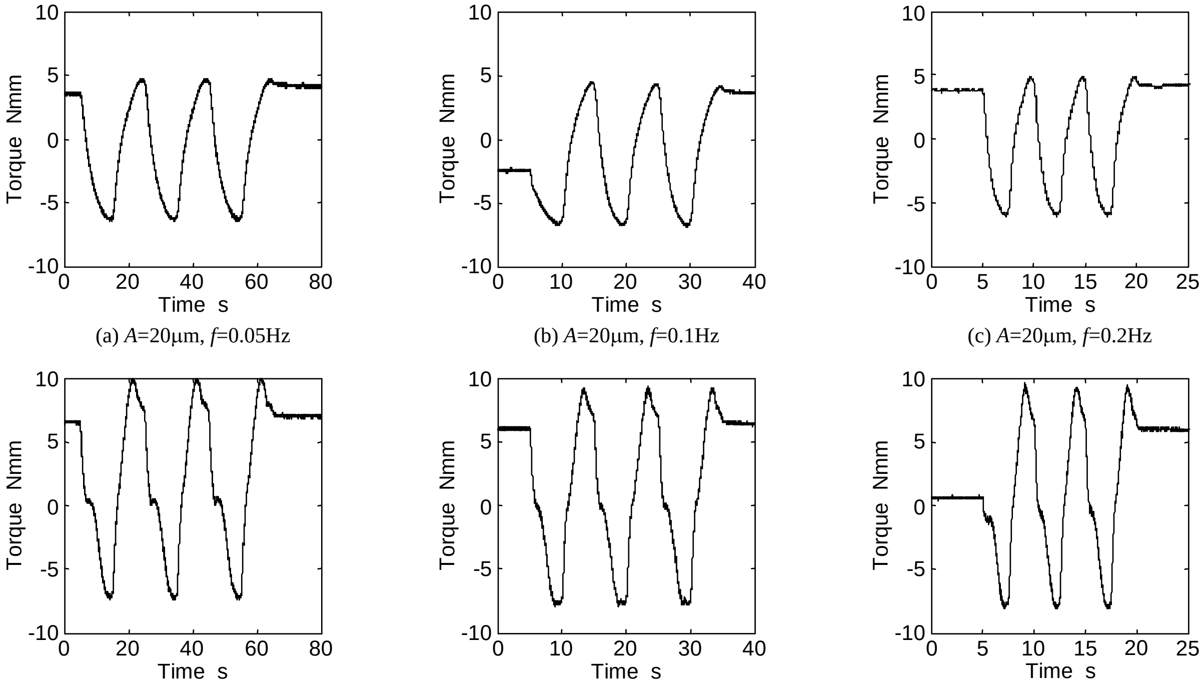
The u_T is the input to the current loop in the amplifier for the AC servo motor. The detail information of the current loop is not clear to the public. In this study, the control system with the current loop is approximated by a first- order lag system and these parameters can be evaluated experimentally. The unknown the viscous damping coefficient C_m in Fig. 2 can be determined by the torque so as to coincide with the experimental result in a circular motion of the motor. Similarly, the coefficients T_m and K_m of the transfer function representing the current loop can be found by the transient response of the motor to the step input. About identification method of these parameters, the reference [4] by coauthor gives more detail information. The parameters for the control system of the AC servo motor are listed in Table 1.

The thrust of this study is on an experimental evaluation of the nonlinear behaviors of the rolling elements in the AC servo motor during microscopic motion. The results indicate that the driving torques were observed when the sinusoidal waves of the microscopic displacement were applied to the AC servo motor. In order to remove the effects of inertial force, the experiments have been performed under the conditions of the low frequency region.

3.1. Driving torques for various input displacements

A series of the experiments ranging from the input amplitudes 0.5 μm (a) to 100 μm (f) for the sinusoidal wave input with the 0.1Hz have been carried out. Fig. 3 (a)~(f) are shown the driving torque curves, respectively. It is very interesting from these figures that the driving torque curves are the exactly same as the sinusoidal waves in case of the smaller input amplitudes such as 0.5 μm and 1 μm, but as the input amplitude increases, the distortion of the sinusoidal waves becomes gradually evident. The magnitudes of torque are 2 Nmm for 0.5 μm, 3 Nmm for 1μm, 7 Nmm for 5 μm, 10 Nmm for 10 μm, 11 Nmm for 20 μm and about 15 Nmm on the average for 100 μm. For the 100 μm and more the magnitudes of torque remains unchanged but the time during the same torque is sustained becomes long.

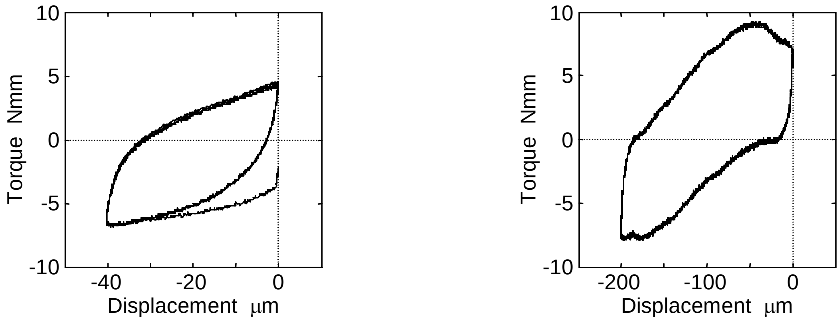
From these results it can be concluded that the driving torque curves to the sinusoidal waves input of microscopic displacement (less than 100μm) are distorted as input amplitude increases.



(a) A=20μm, f=0.05Hz (b) A=20μm, f=0.1Hz (c) A=20μm, f=0.2Hz

(d) A=100μm, f=0.05Hz (e) A=100μm, f=0.1Hz (f) A=100μm, f=0.2Hz

Fig. 4. Driving torques for various input frequencies



(a) A=20μm, f=0.1Hz (b) A=100μm, f=0.1Hz

Fig. 5. Relation between displacement and driving torque

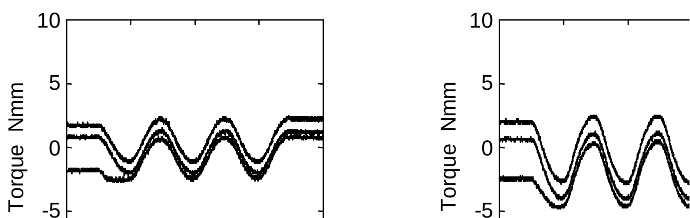
3.2. Driving torques for various input frequencies

Fig. 4 shows different responses of the driving torque to the sinusoidal wave input of microscopic displacement ranging from the input frequencies 0.05 Hz to 0.2 Hz with the input amplitudes of 20 μm and 100 μm.

It can be seen from Fig. 4 (a)~(c) for the input amplitude of 20 μm that coincidence of the driving torque curves can be achieved regardless of the input frequencies. Fig. 4 (d)~(f) for the input amplitude of 100 μm also makes clear that there is no difference among the driving torque curves. From these results it can be concluded that the driving torque curves to the sinusoidal waves input of microscopic displacement depend on the input amplitude only, but not the input frequencies.

Fig. 5 demonstrates the trajectories of the output displacement and driving torque curve measured after the time of three periods has passed. Fig. 5 (a) and (b) show the trajectories obtained from the driving torque curves of Fig. 3(e) and (f) and its output displacement. Therefore, A typical pattern of control operation in our experiments can be described as follows: The input displacement is maintained at the setpoint of 0 mm during 5 s, the input displacement of sinusoidal wave is excited during the time of three periods. Then, the input displacement is put back to the setpoint of 0mm again.

In Fig. 5 (a), the trajectories formed with the output displacement and the driving torque (displacement – torque curve) are the exactly same in the three cycles, expect the transient response from the initial point. In Fig. 5 (b), so the driving torque curves is distorted, the displacement – torque curve is also distorted. But it is obvious that its cycles are exactly same. This means that the displacement – torque curve in microscopic motion shows high repeatability.



3.3. Driving torques for various initial conditions and input displacements

Fig. 6 shows the different responses of the driving torques to the sinusoidal wave inputs of microscopic displacement ranging from 1 μm to 30 μm with the input frequencies of 0.1 Hz. These experiments were repeated three times and started after the motor axis is rotated as the initial condition (torque) changes, respectively.

It can be seen from Fig. 6 (a), (b) for the input amplitude under 2 μm that the driving torques become parallel according to the initial condition. Fig. 6 (c) for the input amplitude of 3 μm, the driving torques become parallel, and are the same as a certain response. Though it doesn't present in the figure, we confirmed that this phenomenon appears in case that the input amplitude ranges from 3 μm to 5 μm, that is considered the transfer area. The analysis of this area will be explained in detail by presentation. Fig. 6 (d)~(f) for the input amplitudes of 10 μm and over also make clear that there are no difference among the initial conditions. It is inferable from these results that the rolling element in the AC servo motor used enters the rolling state in the case that the input amplitude is 5 μm and over. The area where this phenomenon is occurred, it seems to be dependent on the ball's diameter of the rolling element.

4. CONCLUSION

The primary aim of this analysis was to determine the dynamic behaviors of the feed drive system under control based on the small reference of rotation for a precise control of small displacement. This paper examined the control performance of the driving torque of an AC servo motor used in the feed drive system.

The experimental results showed that the distortion of the driving torque curves to the sinusoidal wave input of microscopic displacement becomes gradually evident as the input amplitude increases. It can be concluded that the driving torque depends on the input amplitude, but not the input frequencies. With the particular input amplitude, it can be found that the trajectories for different initial driving torques trace the same pattern after the time of three periods has passed.

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