Self-tuning Control of Brushless Servo Drive for a High Performance Tracking Manipulator

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I. INTRODUCTION

Ensuring reliability and reducing per unit cost are the two fundamental objectives of process automation in manufacturing industry. For pick and place applications, especially in semiconductor manufacturing and packaging industry, accurate positioning is essential in assuring the product quality whereas fast and stable operating speed enables high production rate to be achieved. Accuracy and speed are often two conflicting requirements which are not so easy to attain together. Sometimes a compromise between them is required. To realise a high performance tracking manipulator for high precision and high speed positioning necessitates the use of intelligent variable-speed drive with powerful electric actuator and advanced control algorithm. This is feasible with the recent advancement of both rare earth magnet and microprocessor/DSP-based power electronic drive technologies.

In this study the tracking manipulator for a pick and place application (Fig.1) such as silicon chip handling consists of a PC-hosted DSP-based controller, a driver, feedback devices and an actuator together with associated moving arm and mechanism. The pick and place action is a point to point motion and its required specifications are defined as follows.

a.) Travelling range of 200 mm;
b.) Travelling time within 150 ms;
c.) Accuracy within 10 μm;
d.) Repeatability within 5 μm.

Although only the end point accuracy and repeatability are important in a pick and place action (no specific accuracy is needed to be ensured during motion), it is necessary for the moving arm to follow a pre-defined trajectory at all time within the above specifications to minimise any potential stress on both electrical and mechanical systems.

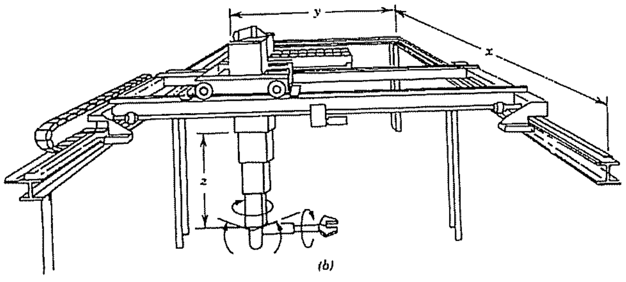

Fig. 1 A typical pick and place application

The stated specifications of travelling distance and time suggest that the required acceleration/deceleration is possibly in excess of 4 G. An actuator or motor of high torque-to-inertia ratio is a necessity and a direct drive is preferable. Among the various types of AC and DC machines, the permanent magnet brushless servo motor has a merit of highest torque-to-inertia ratio. Furthermore, because of no commutation brushes, it has better heat dissipation due to stator winding, no wear and maintenance-free. Therefore, it is most suitable for this type of application. By means of D-Q axis theory, the complex control structure of a brushless servo motor [1] can be transformed into an equivalent DC machine model. This model allows direct control of the motor torque.

For the present system, the performance will degrade due to machine non-linearities (non-uniform airgap and magnetic saturation), parameter variation and non-linear transfer characteristics of the driver. Other system parameters such as moment of inertia may also vary during motion. All these factors will cause de-tuning of the controller which will significantly affect the stability and accuracy of the system. Furthermore, in a continuous process operation, it is not possible to halt the machine and re-tune the control parameters during the process. Hence, a self-tuning mechanism is essential in the control system.

Many types of self-tuning regulators have been published [2,3]. However, most of them are not suitable for this application due to the short motion cycle, high accuracy requirement, and unpredictable trajectory profiles of the semiconductor handling machine. In [2], the proposed algorithm requires sudden halted in the control once a sudden disturbance is encountered. The identification process can only be restarted after the disturbance has disappeared. This process cannot be tolerated in the proposed control system.

The classical concept of dual rate self tuning control has been described in [3]. In this paper, this concept has been further extended to control a brushless servo drive for a performance tracking system.

II. SYSTEM MODELING

The simple lumped parameter model [1] in Fig. 2 can be used to simulate brushless servo motor performance. It can be applied to the steady-state and under the self-tuning control. To calculate the three phase stator winding currents (i_a, i_b and i_c), and hence the torque T, the following equation (1) is used.

$$\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} = \begin{bmatrix} R+sL & sM & sM & sM_{fa} \\ sM & R+sL & sM & sM_{fb} \\ sM & sM & R+sL & sM_{fc} \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \\ I_f \end{bmatrix} \qquad (1)$$

where R Stator winding resistance per phase
L Stator winding self inductance per phase
M Stator winding mutual inductance per phase
M_{fa}, M_{fb}, M_{fc} Mutual inductances between the permanent magnet field and respective phase winding (all are cosine functions of rotor angle with peak value M_f)
I_f Equivalent field current of the permanent magnet field
s Laplace operator

and the terms $sM_{fa}I_f$, $sM_{fb}I_f$ and $sM_{fc}I_f$ represent the stator induced e.m.f. due to the permanent magnets.

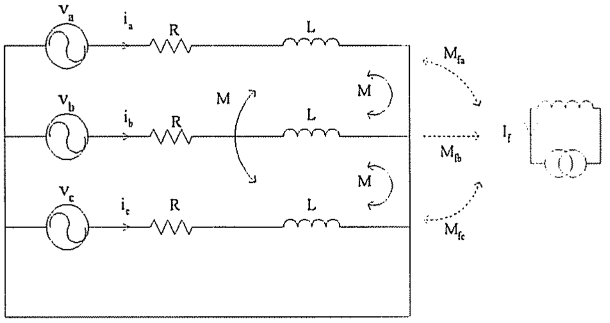

Fig. 2 Electrical model of brushless servo motor

For deriving the required torque regulated structure, equation (1) can be expressed in terms of a D-Q axis matrix as follows

$$\begin{bmatrix} v_D \\ v_Q \end{bmatrix} = \begin{bmatrix} R+s(L-M) & (L-M)\omega & 0 \\ -(L-M)\omega & R+s(L-M) & -M_f\omega \end{bmatrix} \begin{bmatrix} i_D \\ i_Q \\ I_f \end{bmatrix} \qquad (2)$$

where ω Rotor angular speed
v_D, v_Q D and Q axis voltages
i_D, i_Q D and Q axis currents

The torque equation for $i_D = 0$ is given by

$$T = -\frac{3}{2} M_f I_f i_Q \qquad (3)$$

The D-Q axis model can be considered as an equivalent DC motor model which is used in the analysis of the whole system dynamics.

III. DUAL RATE SELF-TUNING CONTROL

Fig. 3 shows the block diagram of the dual rate self-tuning controller. In the figure, *Ref* is the reference signal, *e* is the error signal, T_{sh} is the high sampling time for the inner servo loop while T_{sl} is the low sampling time, u is the output of the controller, and y is the output of the plant. The inner feedback loop has a faster sampling rate than the estimation and design loop.

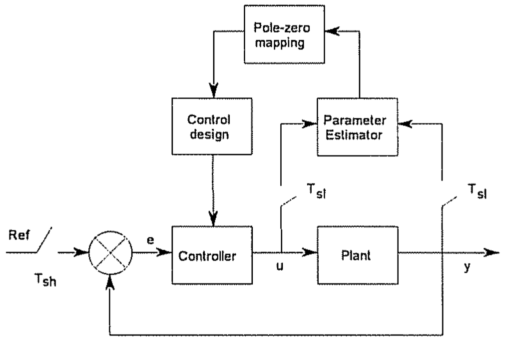

Fig. 3 Block diagram of the dual-rate self-tuning controller.

IV. ON-LINE PARAMETER ESTIMATION

Due to the practical robustness the Recursive Least Squares Estimation (RLSE) as shown in Fig. 4 is used for the on-line parameter estimation based on the input-output data captured from the plant. It is effective and elegant to merely store the estimate calculated $\hat{\theta}(k-1)$ and to obtain the 'new' estimates $\hat{\theta}(k)$ by updating step involving the new observation only. The RLSE algorithm can be summarised as follows:

$$\varepsilon(k+1) = y(k+1) - u^T(k+1)\,\hat{\theta}(k) \qquad (4)$$

$$P(k+1) = P(k)\left[I_p - \frac{u(k+1)u^T(k+1)P(k)}{1+u^T(k+1)P(k)u(k+1)} \right] \qquad (5)$$

$$\hat{\theta}(k+1) = \hat{\theta}(k) + P(k+1)u(k+1)\varepsilon(k+1) \qquad (6)$$

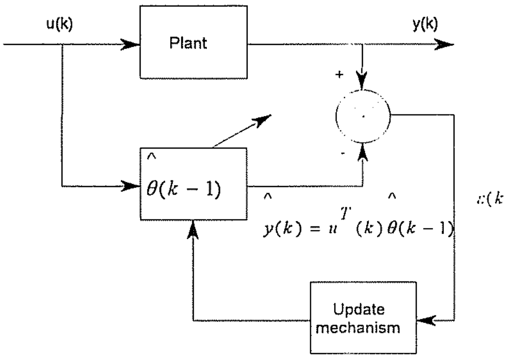

Fig. 4 Block diagram representation of Recursive Least Squares Estimation

V. CONTROLLER DESIGN

A. Tracking controller

As a tracking manipulator for following a position, or velocity, or force trajectory, the main task is to maintain the required system response and accuracy. In our application, a third order filter is used to correct errors due to the resonant frequency and the phase lead/lag of the system. The third order filter can be expressed in terms of :

$$G(z) = \frac{b_0 + b_1 z^{-1} + b_2 z^{-2} + b_3 z^{-3}}{1 + a_1 z^{-1} + a_2 z^{-2} + a_3 z^{-3}} \qquad (7)$$

As the resonant frequency and the phase lead/lag characteristics are time-varying process parameters, it is necessary to have an adaptive mechanism to adjust respective parameters yielding an optimal system performance.

B. Feedforward control and friction compensation

In order to achieve high accuracy and good system response, a feedforward control term and a friction compensator are added to the control algorithm. The feedforward term is proportional to the acceleration and provides an immediate force to overcome the inertia effect. Since friction exists all the time, the friction compensation based on velocity information is used to provide a control force for a better manipulator performance. Both acceleration feedforward and friction characteristics are time-varying as well. It is an advantage to have an adaptive mechanism for estimating the required parameters.

The servo control loop with the self-tuning mechanism can be summarised as follow :

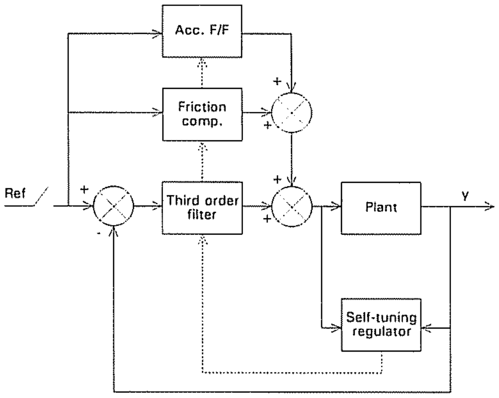

Fig. 5 Block diagram of the closed-loop control with self-tuning mechanism

VI. IMPLEMENTATION

To enable flexibility in testing the self-tuning algorithm while the actual mechanical system is being designed and built, a test jig as shown in Fig. 6 is constructed in our motion laboratory. Motor 1 acts as the actuator of the tracking manipulator for a pick and place application whereas motor 2 acts as a variable dynamic load simulating the characteristics and behaviour of the mechanical system in the presence of external disturbances. The control program is downaloaded into the TMS320C31 Digital Signal Processor (DSP) via the host PC. The DSP executes the control algorithm to receive those feedback signals such as position and speed for self-tuning controller calculation and issue the desired tracking control signal to driver/motor 1. By imposing different dynamic load patterns to driver/motor 2 the characteristics and robustness of the self-tuning regulator can be tested.

Detailed theory and measurement results will be presented in the full paper and at the conference.

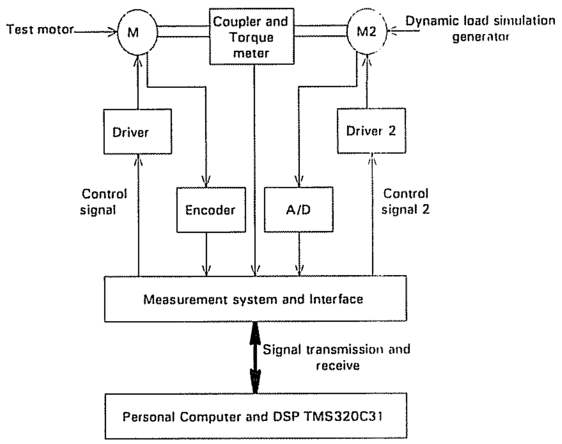

Fig. 6 Block diagram of the dynamic test rig

VII. CONCLUSION

It can be shown that the proposed self-tuning controller could overcome those problems in exhibuted classical control algorithm such as blind spots in off-line tuning and could provide good and consistent system performance. Based on the result of this investigation, further work could be done to extend this control algorithm to other potential applications.

VIII. REFERENCES

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