Magnetic Sensorless Control of Plasma Position and Shape in a Tokamak

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Abstract

Magnetic sensorless sensing and control experiments of the plasma horizontal position have been carried out in the superconducting tokamak HT-7. The sensing is made focusing on the ripple frequency component of the power supply with thyristor and directly from them without time integration. There is no drift problem of integrator of magnetic sensors. Two kinds of control experiments were carried out, to keep the position constant and swing the position in a triangular waveform. And magnetic sensorless sensing of plasma shape is discussed.

keywords: *sensorless control, drift problem, HT-7, shape control, EAST*

1. Introduction

In a nuclear fusion reactor, some kinds of diagnostic systems should be used for reactor protection and plasma control. Since the sensors are used under severe irradiation circumstances, the number of diagnostic sensors placed near by a plasma is desired to be small or zero and must not have a drift problem. Therefore it is important to develop a sensorless sensing or control system in which there are no sensors of the controlled object and need not time integration.

The sensorless control has been developed in two ways. For example, in a device with active magnetic bearings as actuators, the rotor displacement velocity was calculated from the voltage and current in the coil, and the displacement was obtained by integration [1]. On the other hand in an active levitation control, the electromagnet is driven by a pulse width modulated (PWM) signal. The PWM carrier frequency component of the magnetic coil current is a function of the coil inductance. The gap between the electromagnet and the levitated object was calculated directly from the inductance without integration [2].

In this paper, we focus on the application to a plasma horizontal position control system, where the position is controlled by a vertical field coil. The voltage of the power supply for the vertical field coil is controlled by phase shift of the thyristor, and has ripples, whose frequency is higher than that of position controlling current. The ratio of the ripple frequency components of the coil voltage and current is a function of the coil inductance. Since the inductance depends on the plasma horizontal position, the position can be calculated directly from the inductance without integration.

This sensing method has been applied to the superconducting tokamak HT-7. The ratio of the ripple frequency (300 Hz) components of the vertical field coil voltage and current is calculated by Fourier expansion of the wave forms sampled every 0.1 ms for 3.3 ms before and after the time. We calibrated the equivalent circuit parameters in the relation between the ratio and the plasma horizontal position by a least square method. The calculated sinusoidal waveform of the position coincides with the one obtained from flux loop signal. The error is less than 2 % of the plasma minor radius [3].

Using the equivalent circuit parameters calibrated above, feedback control of horizontal position was tested on HT-7 in 2004. Because of real-time control, only past data for each one-ripple period were used to calculate the position based on sensorless sensing. Two kinds of experiments were carried out, to keep the position constant and swing the position in a triangular waveform.

Improvement of the magnetic sensorless control system has been endeavored. And magnetic sensorless sensing of plasma shape is discussed in analogous fashion to the plasma position sensing.

2. Experimental device and magnetic sensorless sensing principle

The superconducting tokamak HT-7 (the toroidal field $B_T = 2.5$ T, the major radius $R = 1.22$ m, the minor radius $a = 0.26$-0.30 m) of ASIPP [4], has thermal radiation shields between the plasma and the superconducting toroidal field coil, and between the toroidal field coil and the vertical field coil. The shield acts as a stabilizing shell for plasma equilibrium and the position is measured by flux loops taking the shell effect into account. The plasma horizontal position is controlled by the vertical field coil power supply, where phase of the thyristor is controlled at the frequency of 300 Hz.

In a feedback control system of the plasma horizontal position x_P, this is controlled by a vertical magnetic field made by vertical field coil current I_V driven by the applied voltage E_V. When the plasma shifts outward horizontally, a voltage is induced in the vertical field coil. In a voltage controlled power supply, I_V is increased, and in a current controlled power supply, E_V is reduced. Therefore we can obtain some information on x_P from the E_V and I_V, and we can deduce the x_P from them.

First, we consider the electrical equivalent circuit equations of the vertical field coil (V), thermal radiation shield (S) and plasma (P), and reduce I_S and I_P from these equations:

$$\begin{pmatrix} Z_V & Z_{VS} & Z_{VP} \\ Z_{SV} & Z_S & Z_{SP} \\ Z_{PV} & Z_{PS} & Z_P \end{pmatrix} \begin{pmatrix} I_V \\ I_S \\ I_P \end{pmatrix} = \begin{pmatrix} E_V \\ 0 \\ 0 \end{pmatrix}$$

$$\left\{ \left(Z_V - Z_{VS}^2 / Z_S \right) - \frac{\left(Z_{VP} - Z_{VS} Z_{SP} / Z_S \right)^2}{\left(Z_P - Z_{PS}^2 / Z_S \right)} \right\} I_V = E_V$$

If we approximate Z as a series element of a resistance and an inductance, and neglect the resistance of the shield and the plasma compared with that of the coil:

$$\frac{E_V}{I_V} = \left((R_V + sL_V) - \frac{(sM_{VS})^2}{(R_S + sL_S)} \right) - \frac{\left((sM_{VP}) - \frac{(sM_{VS})(sM_{SP})}{(R_S + sL_S)} \right)^2}{\left((R_P + sL_P) - \frac{(sM_{PS})^2}{(R_S + sL_S)} \right)},$$

$$\frac{E_V}{R_V I_V} = \left((1 + s\tau_V) - \frac{s \tau_V^{VS} \tau_S^{VS}}{\tau_S} \right) - \frac{s \left(\tau_V^{VP} - \frac{\tau_V^{VS} \tau_S^{SP}}{\tau_S} \right) \left(\tau_P^{VP} - \frac{\tau_S^{VS} \tau_P^{SP}}{\tau_S} \right)}{\left(\tau_P - \frac{\tau_P^{PS} \tau_S^{PS}}{\tau_S} \right)},$$

where s is an operator for Laplace transformation, R, L and M are resistance, self and mutual inductance, and τ is time constant defined as ratio L/R or M/R. Since the plasma inductance and the mutual inductances (M) between the plasma and the others depend on x_P linearly in the first-order approximation concerning elongation ratio and inverse aspect ratio,

$$\frac{E_V}{R_V I_V} = 1 + s\tau_{VS}^{eff} - s\tau_{VP}^{eff}\left(1 + \frac{x_P}{x_0}\right).$$

Consequently, the position (x_P) can be calculated directly from E_V and I_V, and the time integration is not necessary for deriving the position.

The position is expressed as a fractional or a linear function of the ratio (E_V/I_V). But this simple expression results from the above approximate linearization, neglecting the low-frequency components to apply it finally for feedback control of plasma position, since high speed is necessary in detecting the plasma position. On the other hand, since high accuracy is also necessary, we express the position as a first-order lag element of the ratio to raise the degree of precision. The amplitude of the voltage and current ripple is calculated from the fundamental Fourier component of each ripple.

The time resolution of the plasma horizontal position measurement based on magnetic sensorless sensing is limited by the ripple frequency as well as that obtained from the flux loop signal.

3. Experimental results of magnetic sensorless sensing and discussions

In the superconducting tokamak HT-7, the effect of eddy current in the thermal radiation shield must be taken into account. The plasma horizontal position is swept horizontally (the amplitude is smaller than 1 cm) at 7 Hz in the shot number 45160. Since I_S is not measured, we cannot determine the mutual inductances, M_{VS} between the vertical field coil and the shield, and M_{SP} between the shield and the plasma separately. We can determine only the effective mutual impedance (M_{VP} - M_{VS} M_{SP} / L_S) between the plasma and the vertical field coil.

The ratio of the ripple frequency (300 Hz) components of the vertical field coil voltage and current is calculated by Fourier transformation of the waveforms sampled every 0.1 ms. From the equations in the previous section, the ratio is expressed as a fractional function of x_P. But practically a first order transfer function should be sufficient to take into account the resistive effect. The relation between the ratio (impedance) and the plasma horizontal position is calibrated from the waveform of the shot number 45160 from 200 ms to 800 ms, i.e. the gain and time constant of the lag element, and the pedestal are determined.

Using these parameters, we applied this method to evaluate x_P in the shot number 45165, where x_P was swept at the different frequency of 10 Hz. The error of the derived plasma position is lower than 2 % of the plasma minor radius, and only the calculated position in the first cycle just after 200 ms depends on the starting position [3]. Although the error amount of 2 % is sufficient with respect to the required accuracy of the plasma position control, it may be too high with respect to the SOL and with respect to the position of the X-point in a divertor machine. But in the divertor machine, the waveforms of the divertor coil current and voltage would give more information on them, especially on the position of the X-point, and the error amount would decrease.

4. Experimental results of magnetic sensorless control and discussions

In the magnetic sensorless sensing, we have made analysis of the data from HT-7 off-line. In order to apply the magnetic sensorless sensing method to feedback control of plasma position, we must take into account the real time processing, the noise rejection, the accuracy and the calculation time.

Before the calculation of the fundamental Fourier component, necessary is the pre-processing for extracting the ripple component. In the real-time control system, only the past data are available in reducing the low frequency component and the high frequency noise from the raw current signal. The time lag due to the past data should be compensated by adjusting the time constant of the first order lag element. There is a method to utilize the discrete orthogonality of Chebychev polynomial. Since it, however, does not use the data at regular intervals, a simple averaging method is adopted here.

Using the equivalent circuit parameters calibrated above, feedback control of horizontal position was tested on HT-7 in 2004. Because of real-time control, only past data for each one ripple period were used to calculate the position based on sensorless sensing. In the first experiment to keep the position constant, it goes inward linearly in time as shown in Fig. 1. In the second to swing the position in a triangular waveform, it follows outward shift well, but does not inward one as shown in Fig. 2.

The asymmetric behavior suggests an asymmetric cause of sensorless sensing. It may be caused by increase in the ripple frequency as the phase-controlled voltage increases. In this control experiment, however, the calculation of the pre-processing for extracting the ripple component and the fundamental Fourier component were made by fixing the period of the thyristor ripple for simplicity. The easiest way of adjusting the variable period is to input the command signal for constant-voltage control of the power supply for vertical field coil and calculate the period from the time derivative.

The phase of the ripple depends on the firing angle. The amplitude of the current ripple is very small, although that of the voltage ripple is large. The current ripple component depends on the frequency, and the ratio to the main current of low frequency (almost DC) component is about 0.3 %. The small current ripple changes according to the plasma shift via change in the effective mutual inductance. The current ripple changes by 0.2 % per plasma shift of 10 mm. Consequently, the current ripple should be amplified beforehand, so that the plasma displacement dependence on the ripple component could be detected with 12-bit AD converter, or we should adopt with 16-bit AD converter.

The ohmic coil voltage and current are to be measured and analyzed to take the effect into account, although the ripple frequency is 600 Hz, which is two times as high as that of vertical field coil. We should endeavor on making fast the calculation without deteriorating the accuracy. Neural network could shorten the time, although it takes much time for the training.

5. Magnetic sensorless sensing of plasma shape

In order to measure elongation ratio based on magnetic sensorless sensing, we pay attention to quadrupole component of poloidal field coils as in Fig. 3(a). Taking into account the ripple frequency of 300 Hz, we consider the quadrupole current profile in plasma surface and the magnetic coupling with the quadrupole coil component (Fig. 3(b)). As in magnetic sensorless sensing of plasma position, the current ripple component decreases with ripple frequency for fixed elongation ratio of 2 (Fig. 4(a)). For fixed ripple frequency of 300 Hz, the current ripple component changes as a function of the elongation ratio (Fig. 4(b)).

Therefore, magnetic sensorless sensing of elongation ratio is possible in principle. In Fig. 3, the major and minor radii of the quadrupole coil positions are about the same as in HT-7 for comparison with the position sensing. In case of EAST [5], poloidal coils are also superconducting, and the time constant is long. Although the current ripple may be too small, it decays hardly at all in time.

6. Summary

Sensorless sensing experiments were carried out in the superconducting tokamak HT-7. The plasma horizontal position was estimated from the vertical field coil current and voltage. The plasma horizontal position was directly calculated from the ratio of the fundamental Fourier components of the voltage and the current without time integration. Therefore this technique is very advantageous for the application to long pulse tokamak discharges without suffering from the drift problem in time integration of magnetic signals.

In the magnetic sensorless control experiment on HT-7, the plasma position could be controlled stably based on magnetic sensorless sensing method under disturbances from other poloidal coils and thermal radiation shield, if the asymmetric cause of sensorless sensing were eliminated.

Magnetic sensorless sensing of elongation ratio was studied. This sensorless control concept may be extended to the one of triangularity, and resistive wall mode.

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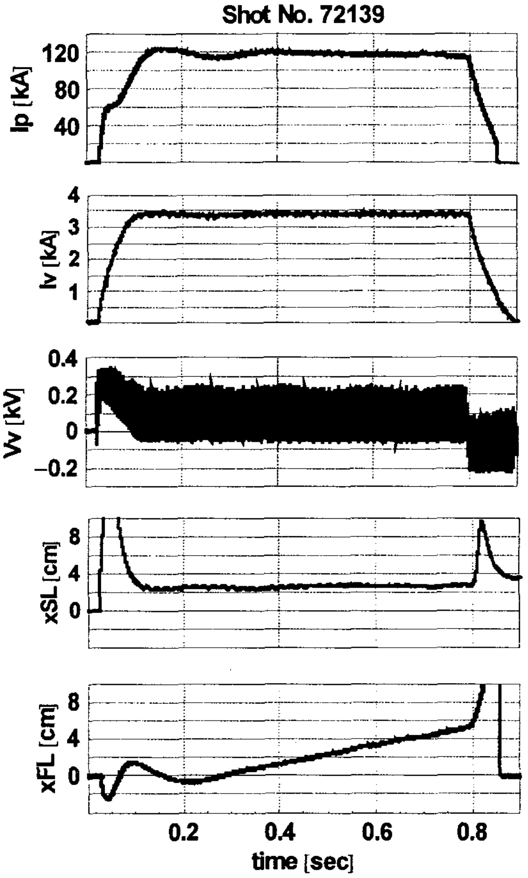

Fig. 1. The first experiment to keep the position constant based on sensorless control. Ip: plasma current, Iv: vertical field coil current, Vv: vertical field voltage, xSL: plasma position based on sensorless sensing, xFL: plasma position deduced from flux loop signal. Although xSL is almost constant by feedback control, xFL goes inward linearly.

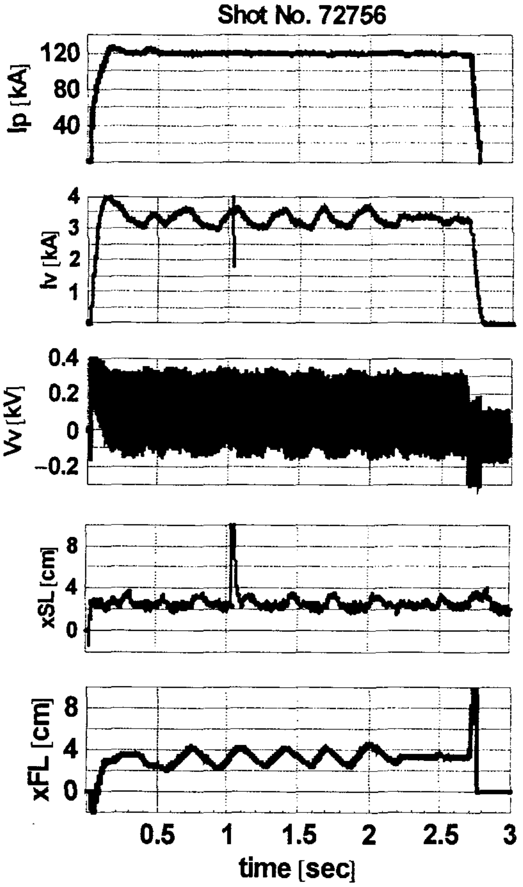

Fig. 2. The second experiment to swing the position in a triangular waveform according to flux loop signal. The notations are the same as in Fig. 2. Although xSL follows outward shift well, it does not inward one.

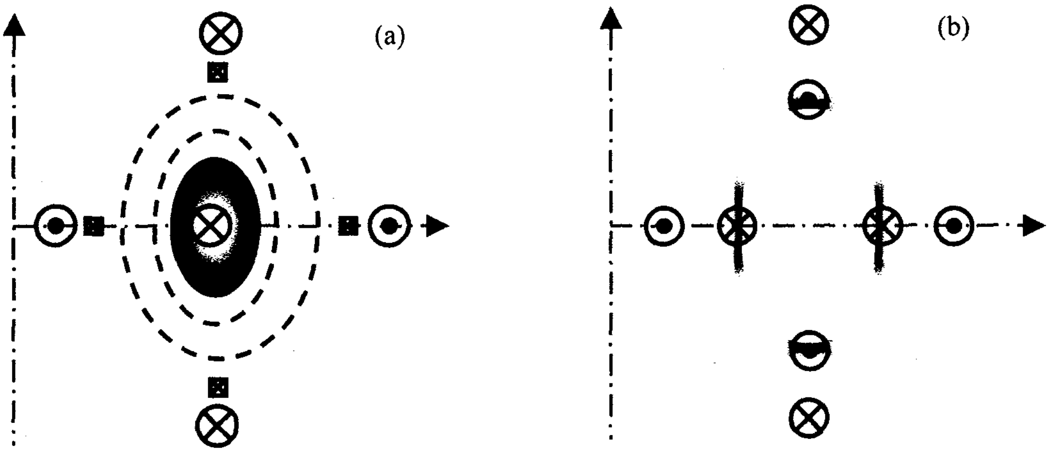

Fig. 3. Poloidal magnetic field is decomposed into dipole and quadrupole (a) field components. Plasma surface current profile is also decomposed into dipole and quadrupole (b) current profile components.

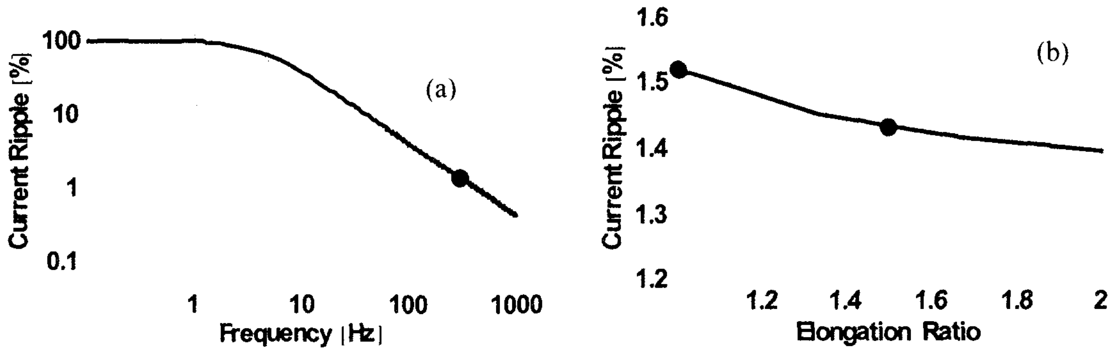

Fig. 4. (a) Current ripple component for fixed κ = 2 is anticipated to be about 1.4 % of DC current for f = 300 Hz. (b) Current ripple component for fixed f = 300 Hz is anticipated to decrease by 0.1 % for increase of 0.5 in *κ*.