DYNAMICS AND FEEDBACK CONTROL OF ISX TOKAMAK*

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ABSTRACT

Perturbation equations of a plasma equilibrium position in a tokamak machine have been developed. Neglecting second and higher order effects, an approximated plasma equilibrium position dynamics function of a tokamak machine is obtained and associated feedback control systems are synthesized.

1. INTRODUCTION

Generation of nuclear fusion energy may be possible in fusion reactors of a tokamak type. A tokamak is a machine having a toroidal configuration, and may be thought of simply as a large transformer having plasma torus as its secondary winding. In order for the plasma torus to achieve a very high temperature required for a fusion reaction to take place, the plasma torus must always remain in the center of a toroidal vacuum vessel surrounding it. To achieve this, the plasma torus must be in a stable equilibrium. Due to the basic nature of plasma torus and design constraints of a tokamak machine, achievement of a stable equilibrium may not always be possible without employment of a feedback control system. Synthesis of a plasma torus position feedback control system for the ISX (Impurities Study Experiment) tokamak requires knowledge of the machine's dynamics and its perturbations. For this reason perturbation equations of a plasma torus equilibrium position in a tokamak machine have been developed taking into account perturbations due to changes in plasma density, temperature, and resistivity, in addition to perturbations due to ohmic heating, vacuum vessel, and plasma circuits. Effects of a transformer iron core and a vacuum vessel characteristic eddy current and penetration time constants have been accounted for. Solution of these perturbation equations results in a plasma equilibrium position dynamics function. Neglecting second and higher order effects, an approximated plasma equilibrium position dynamics function of a tokamak machine is obtained. This dynamics function is used in a study of ISX tokamak plasma equilibrium position stability, and in syntheses of associated feedback control systems.

2. FORCES ACTING ON PLASMA

Plasma is assumed to be a toroidal filament current characterized by its magnitude, its mass per unit length of plasma column, and its (major plasma) radius [1,2].

A sum of five major forces, per unit length of plasma column, is assumed to act on the plasma current mass element in accordance with Newton's law:

Internal expansion force,
Transformer iron core force,
Vacuum vessel eddy current force,
Vacuum vessel induced-current force,
External magnetic field force.

3. INTERACTING ELECTRIC CIRCUITS

Four electric circuits are assumed to be interacting. All circuits are assumed to be characterized by their respective applied voltages, resistances, self-inductances, and mutual inductances. Numbers and subscripts denote circuits and their respective quantities as follows:

Plasma,	1;
Vacuum vessel,	2;
Control field,	3;
Ohmic heating,	4.

Magnetic fluxes involving mutual inductances L_{13} and L_{14} must penetrate the vacuum vessel shell. This fact is taken into account in the appropriate circuit equations [5].

4. PERTURBATION MODEL AND ITS SOLUTION

Perturbation equations of forces and electric circuits form a Perturbation Model of a tokamak. These equations can be used in a computer simulation of plasma's perturbation dynamics. An explicit solution of these equations in a symbolic form, however, would be of a complexity rendering it useless for any desired analytical study or design. For such a purpose simplified approximated solutions must be considered.

5. ISX DYNAMICS FUNCTION

An approximated solution of a simplified Perturbation Model results in a plasma motion dynamics (transfer) function [7]

$$\Delta(S - S_1)(S - S_2) = -V_3 G_1 (1 + \tau_r S) \qquad (1)$$

where

$$S_2 = \frac{S_{22}}{1 - S_{22}\,\tau_r} \qquad (2)$$

$$G_1 = \frac{G_0}{1 - S_{22}\,\tau_r} \qquad (3)$$

Δ (meter) is the plasma current mass element displacement,

V_3 (volt) is the magnetic control field coil voltage,

τ_r (sec) is the vacuum vessel eddy current delay time constant,

S_1(sec^{-1}), S_{22}(sec^{-1}), and G_0(meter/volt sec^2) are functions of plasma and tokamak machine parameters.

It is observed that roots (poles) of the plasma motion dynamics function, S_1 and S_2, must be real-negative for plasma equilibrium position stability.

Using ISX tokamak numerical data, for radial plasma motion root S_1 is a real-positive, equal to 1.4, and is therefore an unstable root. Considering expected variations and accuracy of the numerical data, however, this root may also be real-negative. Therefore, for radial plasma motion the root S_1 may or may not be a stable root, depending on design uncertainties of a tokamak machine and its operating conditions.

For axial plasma motion the root S_1 is real-negative, equal to -43.5, and is therefore a stable root.

Considering root S_2, Eq. (2), it is noted that at $\tau_r = 0$ it is equal to S_{22}. Using ISX numerical data,

radial $S_{22} = -1168.1$ is a stable root,

axial $S_{22} = +502.5$ is an unstable root.

Both of these roots are operated on by τ_r, Eq. (2), to produce stable radial and axial roots, S_2.

According to Eq. (2), initially stable radial root S_{22} produces a stable radial root S_2 for any value of τ_r. Therefore radial plasma equilibrium position of the ISX tokamak may or may not be stable, depending entirely on radial root S_1, as discussed previously. An initially unstable axial root S_{22} is converted to a stable axial root S_2 only if

$$\tau_r > \frac{1}{\text{unstable axial } S_{22}} \qquad (4)$$

and since axial $S_{22} = +502.5$, the vacuum eddy current delay time constant must be

$$\tau_r > 2.0 \times 10^{-3} \text{(sec)}$$

Among the several estimated ISX tokamak parameters a value of

$$\tau_r = 5.24 \times 10^{-3} \text{(sec)}$$

has been arrived at. Therefore axial plasma equilibrium position of ISX tokamak is expected to be stable.

6. PLASMA POSITION FEEDBACK CONTROL SYSTEM

A single loop Plasma Equilibrium Position Feedback Control System designed for ISX tokamak is shown schematically in Fig. 1 [3-5, 8, 9].

The magnetic control Field Drive is a single loop feedback system in itself [8]. Its transfer function was found to be of the first over first order, τ_4 being approximately a time constant of the magnetic control field coil, while τ_5 is approximately equal to 1.5 msec and is different from zero by virtue of Field Drive hardware design. Gain constant of the Field Drive transfer function is approximately equal to unity.

The Dynamics Function has been discussed briefly in the preceeding section [7].

The Forward and Feedback Functions, their gain and time constants have been computed such that the closed loop natural frequency of both the radial and axial Feedback Control Systems is 1000 radians per second, and their step-function responses have negligible overshoots, less than 1.0% [8,9]. Computations have been performed under an assumption of an ideal (unity transfer function) plasma position (shift) measurement [3, 4, 6].

A theoretical design step-function response of the radial Plasma Equilibrium Position Feedback Control System is shown in Fig. 2, while its actual hardware step-function response is shown in Fig. 3. It is noted that, discounting minor plasma disruptions and measurement noise, they are practically identical. An actual hardware axial Plasma Equilibrium Position Feedback Control System is expected to perform just as well.

7. CONCLUSION

A simple and useful plasma motion dynamics function of a tokamak has been derived. This function has been used for syntheses of the required radial and axial Plasma Equilibrium Position Feedback Control Systems. Theoretical design and actual hardware step-function responses of the radial Plasma Equilibrium Position Feedback Control System are shown to be identical for all practical purposes.

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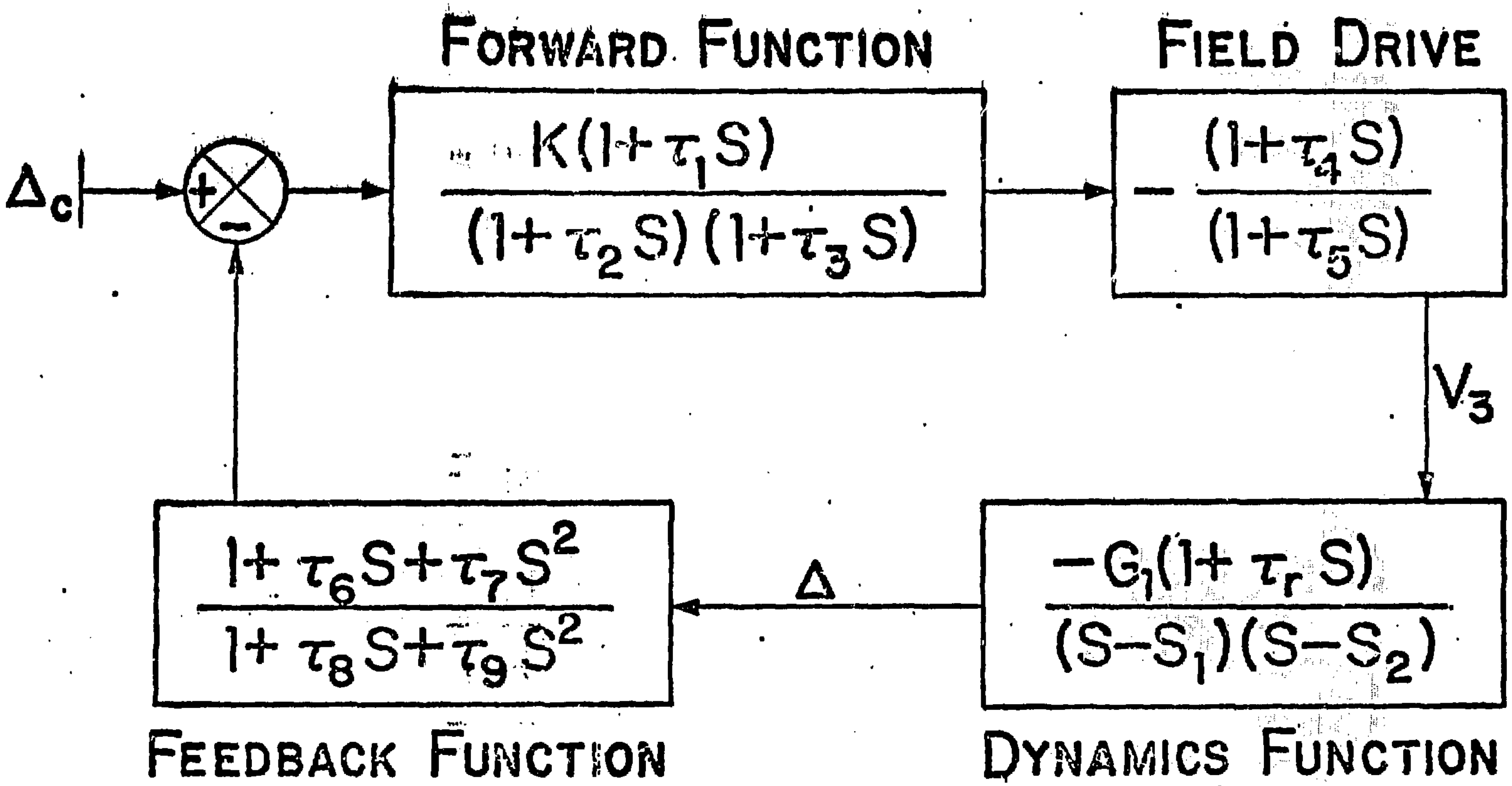

FIG.1. Plasma Equilibrium Position Feedback Control System, Radial and Axial.

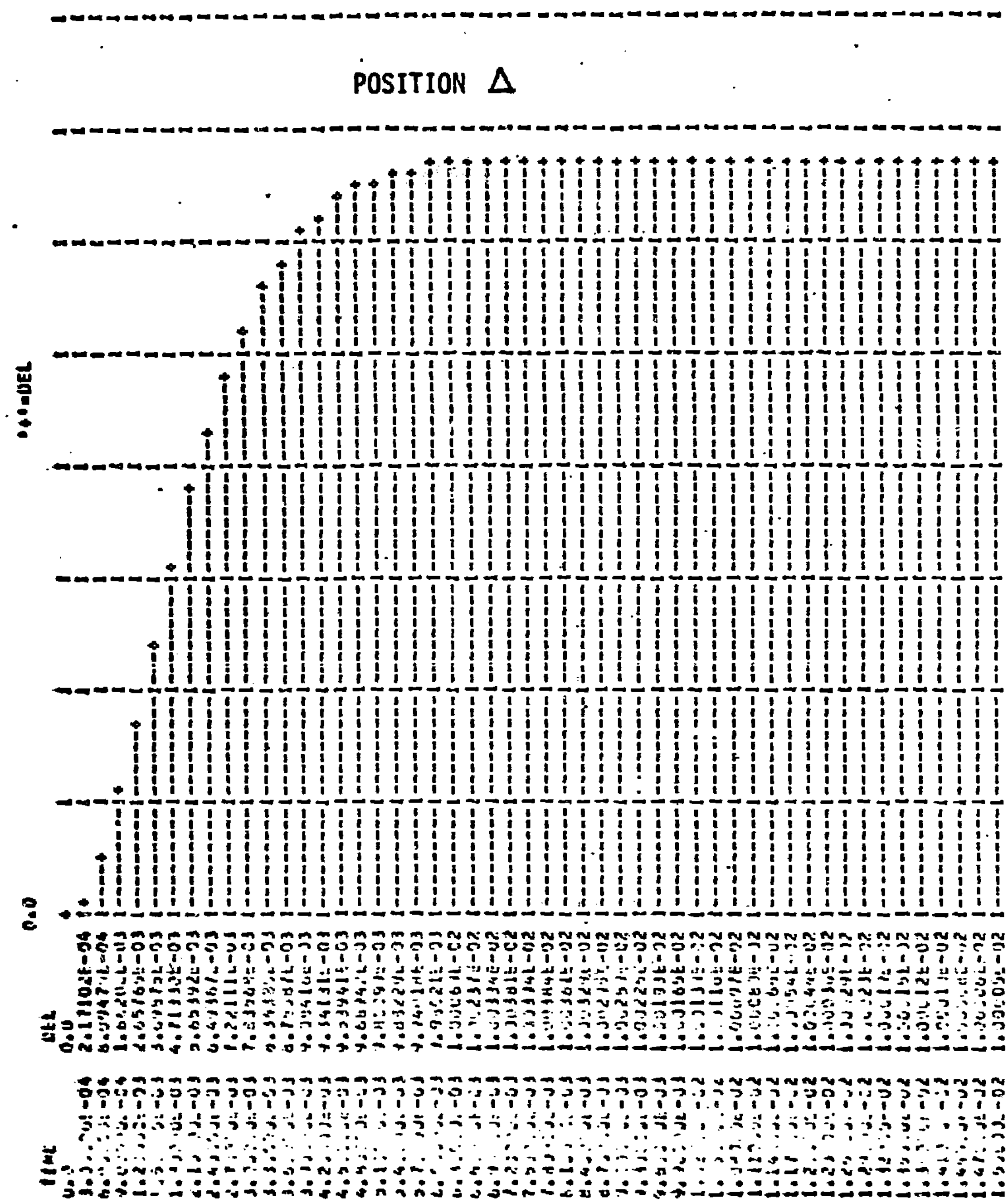

FIG.2. Theoretical Design Step-Function Response, ISX Radial Plasma Equilibrium Position Feedback Control System.

To be enlarged and traced over.

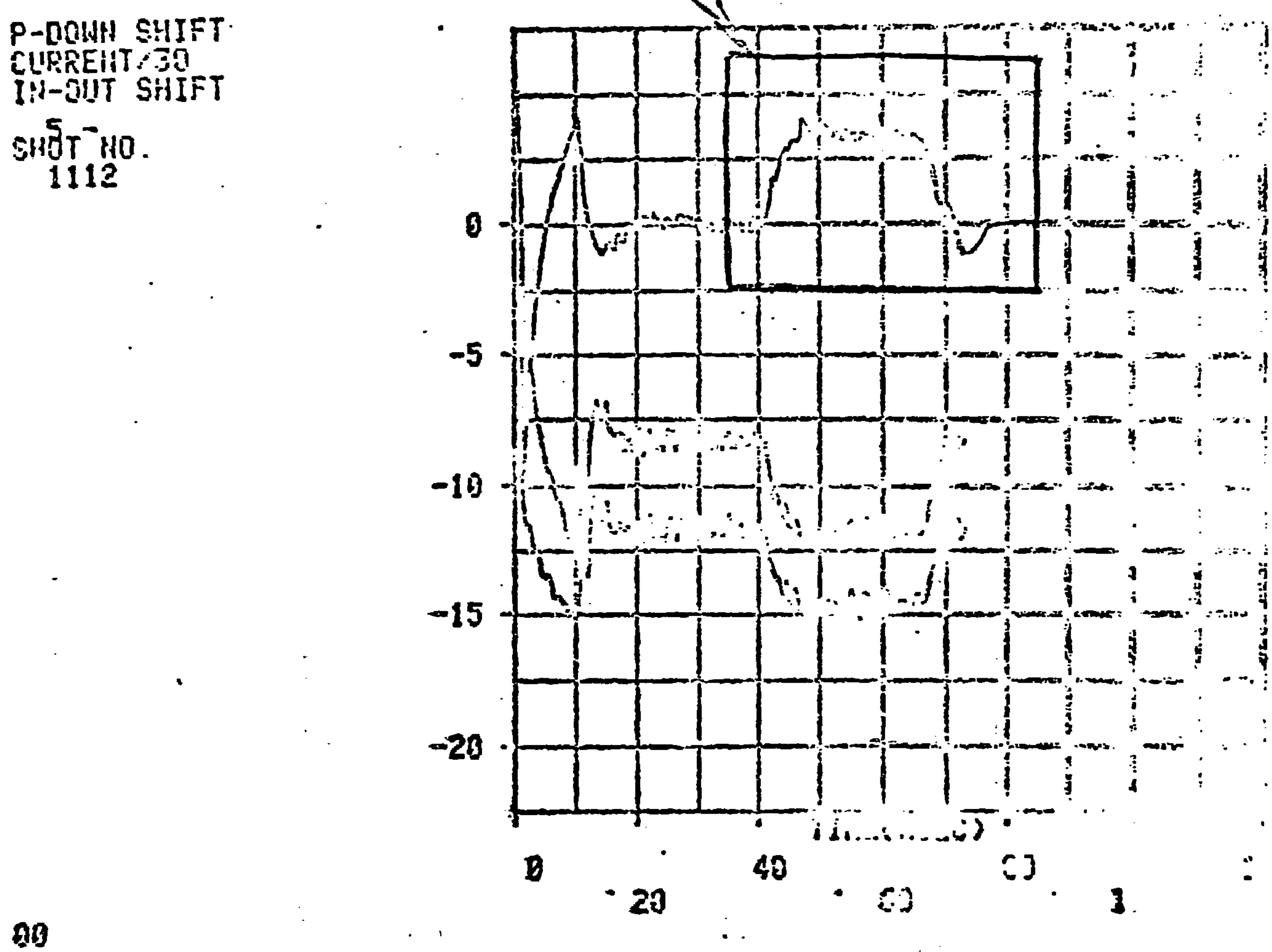

FIG.3. Actual Hardware Step-Function Response, ISX Radial Plasma Equilibrium Position Feedback Control System.