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Feedback controller for saddle coils for suppression of resistive wall modes in EXTRAP T2R

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Introduction

Resistive wall modes (RWM) predicted by linear MHD theory [1] are experimentally observed in EXTRAP T2R reversed field pinch (RFP) device. Modes are non-resonant, non-rotating (different from rotating resonant modes in tokamak devices) with growth rates that are in agreement with theory [2]. EXTRAP T2R is a thin shell, medium size RFP ($R/a = 1.24/0.18$ m) with typical discharge pulse length $t_d = 15 - 23$ ms about three to four times the shell vertical field penetration time of $\tau_v = 6.3$ ms [3]. An active feedback control system is used in EXTRAP T2R to suppress RWM's.

Intelligent shell is one possible stabilization scheme. Intelligent shell attempts to keep the radial magnetic flux zero at the positions of the sensor coils underlying the active coils. In these experiments on EXTRAP T2R each active coil is driven by a professional audio amplifier whose input is produced by an analog PID controller using the sensor coil output. An array of 64 active coils at 4 poloidal and 16 toroidal positions is used. An array of 256 flux loops at 4 poloidal and 64 toroidal positions is used to measure the radial component of the magnetic field. The loops that coincide with the positions of the active coils are used as sensors.

An analog controller has been developed for the intelligent shell operation. A model of the active feedback system was made and compared to the experimental data. Initial experimental results on active feedback using the intelligent shell scheme were obtained.

RWM feedback system in EXTRAP T2R. Analog PID controller

The intelligent shell feedback scheme is modelled in EXTRAP T2R as is shown on Fig.1. Reference signal is zero since intelligent shell tries to keep the flux zero at the position of the sensors under the active coil. Output signal S from the sensor coil is the sum of the radial magnetic fields produced by plasma and the active coil. Sensor output S is input to the analog PID (proportional-integral-derivative) controller which produces the control signal U to the amplifier that drives the active coil so as to create the cancelling radial magnetic field. For the present analysis the plasma field inputs as a perturbation added to the system. The resistive shell is also included in the sheme. It acts basically as a low pass filter.

An important part of the feedback system is the analog PID controller, which produces the control signal for suppression of RWM's. Properties of the PID controller can be studied from a so called transfer function that is a relation between output and input signals of the PID controller. In time domain the PID controller can be described by the equation:

$$u(t) = G_p e(t) + G_i \int e(t)dt + G_d \frac{de(t)}{dt} \tag{1}$$

where $u(t), e(t)$ are controller output and input signals respectively. It is more convenient

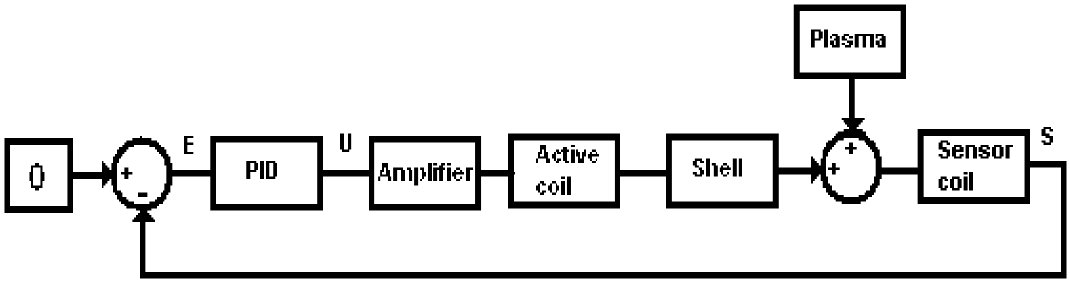

Fig. 1. Intelligent shell RWM feedback system in EXTRAP T2R

to work in Laplace space. Then the transfer function can be written as:

$$F(s) = \frac{U(s)}{E(s)} = G_p + G_i\frac{1}{s} + G_d s \tag{2}$$

Here G_p, G_i, G_d are the proportional, integral and derivative gains of the controller respectively and s is the Laplace variable. In the experiment the transfer function of the PID controller is given by:

$$F(s) = (g_p + g_i\frac{1}{s} + g_d s) * g_0 \tag{3}$$

Here g_p is constant and g_i, g_d, g_0 can be changed independently.

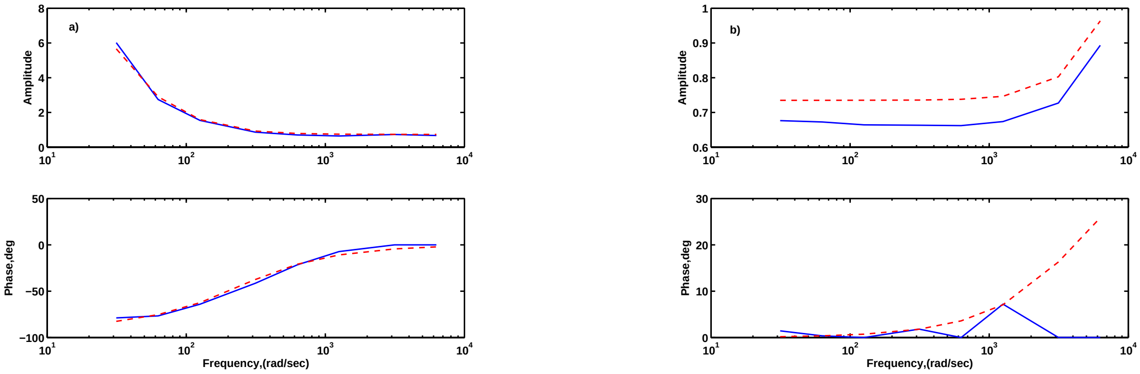

Fig. 2. The transfer function of the analog PID controller: a)PI controller ($G_p = 0.75, G_i = 0.06, G_d = 0.0$), b)PD controller($G_p = 0.75, G_i = 0.0, G_d = 1.0$). Measured (solid line) and model (dashed line) results are shown.

The transfer function F of the PID controller was measured in EXTRAP T2R. Results of the measurements are shown on Fig.2 as solid lines. Experimental results were fitted and a model of the PID controller was obtained. Results of the modelling are shown on Fig.2 as dashed lines. Amplification of low frequency part (Fig.2a) and amplification of high frequency part(Fig.2b) represent integral and derivative effects of the controller on the input signal. Values of G_p, G_i, G_d in the model show the absolute controller gains used in the experiment. They are obtained multiplying g_p, g_i, g_d by g_0 (eq.3).

The transfer functions of the different components of the feedback system (amplifier, active coil, shell, sensor) were measured and modelled. These transfer functions are given by the equations:

$$F_{ampl}(s) = G_{ampl} * \frac{(s+5)^2}{(s+10)^2}\ [V/V],\ G_{ampl} = 8.5$$
$$F_{coil}(s) = G_{coil} * \frac{1}{1+\tau_{lr}s}\ [T/V],\ G_{coil} = 1.2 * 10^{-2}, \tau_{lr} = 0.001 \text{ sec}$$
$$F_{shell}(s) = G_{shell} * \frac{1}{1+\tau_{sh}s}\ [T/T],\ G_{shell} = 1.0, \tau_{sh} = 0.0015 - 0.0025 \text{ sec}$$
$$F_{sensor}(s) = G_{sensor}\ [V/T],\ G_{sensor} = 7.2 * 10^2$$

where $G_{ampl}, G_{coil}, G_{shell}, G_{sensor}$ are the gains of the components. Dimensions of the output and input signals are shown in square brackets.

Stability of the closed loop system can be studied from the model. On Fig.3 a root locus of the system is plotted for the controller settings that are typical in the experiment. Real and imaginary parts of the closed loop poles that determine stability of the system are shown in the complex plane. Curves represent changes in the values of the closed loop poles with change of the g_0 value. In practice the value of real part determines the settling time of the system and the value of imaginary part shows the oscillation frequency of the system. The system becomes unstable when real part of the closed loop poles becomes positive (curves enter right half plane). As can be seen from Fig.3 the local active coil system in EXTRAP T2R is stable for all reasonable values of g_0 (the curves stay in left half plane). Increase in g_0 increases absolute value of real part of the closed loop poles pointing to the shorter settling time. Increase in imaginary part with increasing g_0 shows higher oscillation frequency of the system.

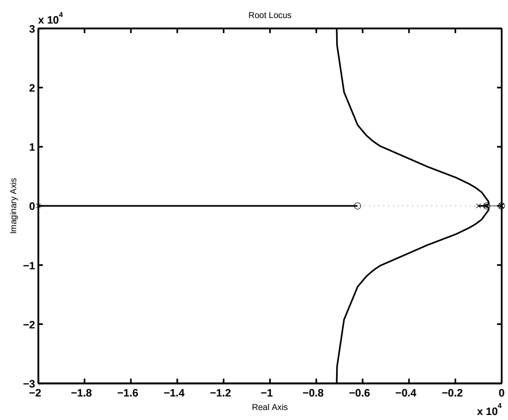

Fig. 3. The root locus of the feedback system. Real axis-real part of the closed loop poles,imaginary axis-imaginary part of the closed loop poles. Lines show dependence of the closed loop poles on g_0.The controller gains are: $g_p = 5.0, g_i = 1.5, g_d = 10$

Comparison of experimental results with model

In order to check how well the model describes the real system comparison with experimental results was made. The RWM time evolution is relatively shot-to-shot reproducible in experiment, therefore two discharges were used, one with feedback and one without to make comparison with the model. The plasma magnetic field measured by the sensor coil in the discharge without feedback was used as the input to the model. The output from the model was compared with the sensor coil signal from the discharge with feedback. The same controller gains g_p, g_i, g_d as for the stability analysis were used with $g_0 = 1.5$ The results are shown on Fig.4. Good agreement between the model and the experimental data is seen.

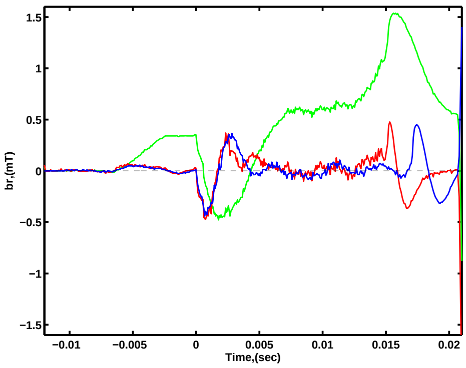

Fig. 4. Comparison of the experimental data and the model. Green-the sensor coil signal without feedback; blue-the sensor coil signal with feedback; red the model output. The absolute gains used for the PID controller model are: $G_p = 7.5$, $G_i = 2.3$, $G_d = 15$.

Initial experimental results

Using the developed analog PID controller initial experimental results on active feedback were obtained. These results are shown on Fig.5. The controller gains used for this experiment were: $g_p = 5.0$, $g_i = 1.5$, $g_d = 10$, $g_0 = 10.5$. The plasma current shown on Fig.5a is similar for the two discharges showing shot-to-shot reproducibility. Fig.5b shows the radial magnetic field measured by the sensor for the discharges with and without feedback. The active coil current for the same discharges is shown on Fig.5c. Good suppression of the radial magnetic field at the sensor radius is seen. At the same time oscillations of the active coil current show the action of the feedback system that produces the cancelling radial magnetic field.

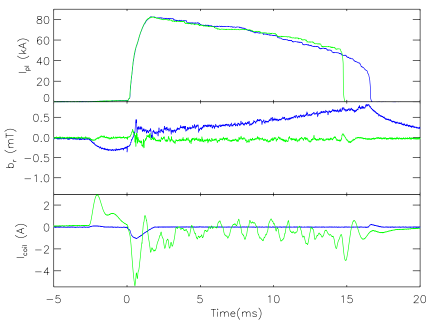

Fig. 5. The plasma current,the radial magnetic field and the active coil current with (green) and without (blue) feedback

Summary

An analog PID controller has been developed for suppression of resistive wall modes in EXTRAP T2R. The transfer function of the PID controller was measured and modelled. The transfer functions of the different parts of the system (amplifier, active coil, shell, sensor) were obtained. Stability of the closed loop system was discussed. The model of the closed loop system was compared with the experimental results showing good agreement. Initial experimental results show good cancellation of the radial magnetic field at the positions of the sensors under the active coils.

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