FEEDBACK STABILIZATION OF THE AXISYMMETRIC
INSTABILITY OF A DEFORMABLE TOKAMAK PLASMA

N. Pomphrey and S.C. Jardin

Plasma Physics Laboratory, Princeton University

P. O. Box 451

Princeton, NJ 08544

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ABSTRACT

We analyze the magnetohydrodynamic (MHD) stability of the axisymmetric system consisting of a free boundary, non-circular cross-section tokamak plasma, finite resistivity passive conductors, and an active feedback system with magnetic flux pickup loops, a proportional amplifier with gain G , and current carrying poloidal field coils. Numerical simulation of a system that is unstable with $G = 0$ shows that for some placements of the pickup loops, the system will remain unstable for all values of G , while for other placements of the loops, the system will be stable for $G > G_{crit}$. This behavior is explained by analysis using an extended energy principle, and it is shown to result from the deformability of the plasma cross section.

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1. INTRODUCTION

It is well known that elongated cross-section tokamak plasmas are subject to a pernicious axisymmetric MHD instability and must be stabilized by the placement of nearby passive conductors, and by an active feedback system which responds on the resistive time of these plates [1,2]. Most previous analyses of the stability of such a feedback system have considered the case of a deformable plasma stabilized by perfectly conducting passive conductors only [1,3], or the case of a rigid filamentary plasma with resistive conductors and an active feedback system [2]. Here we discuss important new effects present in the more realistic system consisting of a finite-size deformable plasma, resistive conductors, and an active feedback system. We also discuss the importance of the low-frequency limit of this system in which the resistive conductors do not enter.

The components of an active feedback system include: (1) a means of observing the plasma motion; for example, magnetic flux pickup loops, (2) a set of current carrying feedback coils positioned so that they produce a magnetic field which opposes the unstable plasma motion, and (3) an amplifier system which transforms the observed flux measurements into a voltage signal at the coils. It is clear that the placement of the feedback coils is important. However, we will show in this letter that the correct placement of the flux loops is equally critical; an incorrect placement can fail to stabilize the vertical mode no matter how large the feedback gain is. We demonstrate this effect by analyzing the results of a numerical simulation relevant to the Princeton Beta Experiment [4,5]. Analysis is by means of Bode diagram and Nyquist techniques. Similar results are found in an analytic calculation which applies the energy principle of ideal magnetohydrodynamics to a straight plasma with rectangular cross section and constant current

density. The successful design of feedback systems for future experiments must consider the correct placement of flux pickup loops as a critical issue.

2. NUMERICAL SIMULATION RESULTS

Figure 1 shows a schematic of a shaped plasma for which position control is a necessary element of the design. The plasma carries 0.75 MA current, and has a cross section that is elongated and indented on the inboard side. Conducting plates surround the plasma, which effect passive stabilization on the ideal MHD time scale. The L/R time for the passive conductors is 100 msec. The poloidal field coil system used for equilibrium, shaping, and feedback control is shown, as are two pairs of observation points. The flux difference between any one of these pairs is a measure of the displacement of the plasma from its equilibrium position on a midplane. Apart from the location of these pickup loops, the system shown in Figure 1 is an accurate representation of the modified Princeton Beta Experiment (PBX-M) [6].

We have used the Princeton Tokamak Simulation Code (TSC) [7] to analyze vertical position control issues for the configuration described above. The TSC accurately models the transport time-scale evolution of axisymmetric plasmas, including the plasma interaction with passive and active feedback systems. For the simulations described below, we use a simple feedback system where an incremental voltage is supplied to the vertical feedback coils in proportion to the measured flux imbalance between one of the observation pairs. i.e.,

$$V_{fb}(t) = B \Delta\psi_{i,i+1}(t), \quad i = 1 \text{ or } 2 \quad (1)$$

When the gain, B , is zero so that the feedback system is turned off, the

growth time of the vertical instability is calculated by TSC to be 47 msec. This time, which is calculated from a fit of the time rate of change of $\Delta\psi_{i,i+1}(t)$ to an exponential, is independent of which observation pair is used. We now show that although both observation pairs detect the motion, only the outboard pair can be successfully incorporated into the feedback scheme to achieve complete motional stability.

To investigate the stability of the feedback system, we adopt some techniques of control engineering [8]. Figure 2 is a block diagram for the system; it shows the relationship between components, and the flow of signals from input to output. A reference voltage signal is input to the vertical feedback coils, the plasma/conductor/vacuum MHD equations are advanced by TSC, and the measured flux difference between a pair of observation points is output. The feedback loop is closed by amplifying the output, and returning it to the feedback coils as a voltage correction to the reference signal. For stability, all poles of the closed-loop transfer function $T(s) = G(s)/[1+SG(s)]$, must have negative real parts. The location of these poles is determined by the encirclement theorem, which leads to the Nyquist criterion for stability:

$$\left(\frac{1}{2\pi}\right) [\Delta\arg(1 + SG(s))]_{-i\infty}^{+i\infty} = N_p \quad (2)$$

The phase change of the transfer function on the left hand side can be interpreted as the number of counter - clockwise encirclements of the point $(-1,0)$ by the $SG(s)$ locus as s is increased from $-i\infty$ to $+i\infty$, and N_p is the number of poles of $SG(s)$ having positive real parts. For a vertically unstable plasma stabilized by resistive walls, it is possible to show that $N_p = 1$.

The open-loop transfer function, $G(s)$, is not expressed in closed form for our problem, and must be evaluated numerically. To do this, we input a test signal to the feedback coils in the form of a sinusoid with frequency ω . The steady state response characteristics of a stable system are such that $|BG(i\omega)|$ = amplitude ratio of the output and input sinusoids, and $\arg [BG(\omega)]$ = phase shift of the output sinusoid with respect to the input sinusoid. The data is collected on opposite sides of the summing point (see Fig. 2).

In Fig. 3, we present results obtained from running the TSC using first the inboard, and then the outboard observation pair for monitoring the flux. The gain is the same for both cases. Results are shown as a Bode diagram, which consists of two graphs. One is a plot of $\log |BG(i\omega)|$ versus ω , the other is a plot of $\arg[BG(i\omega)]$ versus ω . Once the Bode diagram is constructed, the Nyquist plots follow readily. We see that use of the outboard observation pair gives rise to a closed curve which meets the conditions required by the Nyquist stability criterion. On the other hand the Nyquist curve obtained using the inboard observation pair not only fails to enclose the point (-1.0) , but it is also described in the wrong sense. Since changing β simply scales the distance of each point on a curve to the origin, but leaves the sense of traversal unchanged, the feedback system which uses the outboard observation pair will be stable for a finite range of β , corresponding to the enclosure of (-1.0) , whereas the feedback system which uses the inboard observation pair will be unstable for all values of β .

The essential difference in behavior of the two feedback systems is the response to low frequencies. At very high frequency the signal from the feedback coils is unable to affect the plasma motion because it cannot penetrate the intervening passive conductors. The feedback system is completely passive in this limit. If the frequency is lowered to become

comparable to the inverse L/R time of the conductors, the signal has time to influence the plasma motion. The influence is seen in the Bode plots as a dramatic change in slope in the curves of amplitude and phase. When we lower the frequency toward the zero frequency limit the contrast between using the different observation points is most clear. In this limit, the passive stabilizers are completely transparent to the feedback signal, and therefore cannot affect the feedback response of the plasma. We now investigate this limit with an analytic model.

3. ANALYTIC MODEL

A constant current density, rectangular cross section, straight plasma column is unstable to a non-rigid axisymmetric ($n = 0$) instability [9]. Here we modify the analysis of reference [9] to include an active feedback system, and we show that there are forbidden regions for the placement of the pickup loops if stability is to be ensured. For the straight plasma, the equilibrium poloidal flux, ψ , satisfies $\nabla^2 \psi = j_z$. We choose $j_z = \text{constant}$, and

$$\psi = r^2 + \alpha r^4 \cos 4\theta \quad . \quad (3)$$

Here, α is a squareness parameter, which is assumed to be small. If $\alpha = 0$, then the plasma-vacuum interface ($\psi = 1$) is a circle. Even modest values of α , such as $\alpha = 0.2$, make the $\psi = 1$ surface nearly square. Figure 4 shows a schematic of the plasma, the poloidal field coils, and typical pairs of observation coils.

The δW of the energy principle can be written as separate contributions from the plasma and from the vacuum:

$$2 \delta W = \int_p [(\nabla \phi_p)^2 + j_z \xi \cdot \nabla \phi_p] dA - \int_{pv} \phi_v \frac{\partial \phi_v}{\partial n} dS \quad (4)$$

where ϕ is the perturbed flux function, ξ is the fluid displacement, and the subscripts p, v, and pv refer to plasma, vacuum, and the plasma vacuum interface respectively. To evaluate this expression for the given model, it is convenient to express δW in terms of the flux coordinates (ψ, θ, z) . Thus, we write

$$2\delta W = \iint d\psi d\theta \oint (\nabla \phi_p)^2 - j_z \oint d\theta \oint \phi_p^2 - \oint d\theta \oint \phi_v (\nabla \psi \cdot \nabla \phi_v) \quad (5)$$

where

$$(\nabla \phi_p)^2 = (\nabla \psi)^2 \left(\frac{\partial \phi_p}{\partial \psi} \right)^2 + 2 \nabla \psi \cdot \nabla \theta \left(\frac{\partial \phi_p}{\partial \psi} \right) \left(\frac{\partial \phi_p}{\partial \theta} \right) + (\nabla \theta)^2 \left(\frac{\partial \phi_p}{\partial \theta} \right)^2 \quad (6)$$

and

$$\oint = (\nabla \psi \cdot \nabla \theta \times \nabla z)^{-1} = \frac{1}{2} \frac{dr^2}{d\psi} \quad (7)$$

is the jacobian. The integral denoted $\oint$ is evaluated around the $\psi = 1$ contour, and $j_z = 4$ in the units of Eq. (3). Since α is small, Eq. (3) can be inverted to obtain $r(\psi, \theta)$, from which the metric elements and the jacobian can be evaluated.

The procedure for evaluating δW follows closely the description given in Ref. [4] but with the perturbed vacuum flux modified by the presence of current carrying feedback coils. Thus, we take the perturbed vacuum flux to consist of a homogeneous piece satisfying $\nabla^2 \phi_v = 0$ and an inhomogeneous piece as follows:

$$\phi_v = B_1 r^{-1} \cos \theta + \sum_{m=1}^{\infty} (\alpha B_m^{\alpha} + \alpha^2 B_m^{\alpha\alpha}) r^{-m} \cos m\theta + \phi_{fb} \quad (8)$$

Here

$$\phi_{fb} = \sum_{i=1}^N I_i \ln |r - R_i| \quad (9)$$

is the contribution from N feedback coils.

We expand the feedback contribution in multipoles; thus,

$$\phi_{fb} = \sum_{m=1}^{\infty} (\alpha L_m^{\alpha} + \alpha^2 L_m^{\alpha\alpha}) \cos m\theta \quad (10)$$

Each harmonic is interpreted as the flux from an equivalent feedback system with m identical coils, equally spaced on a circle about the plasma center. (The L_0 terms are absent because they have zero gradient).

In the plasma, the perturbed flux is of the form

$$\phi_p = H_1(\psi) \cos \theta + \sum_{m=1}^{\infty} (\alpha H_m^{\alpha}(\psi) + \alpha^2 H_m^{\alpha\alpha}(\psi)) \cos m\theta + \alpha^2 \psi H_4^{\alpha}(\psi) \quad (11)$$

where the constant piece comes from the incompressibility constraint.

Final results are expressed in terms of the Fourier components of the flux on the plasma boundary, which we write as $D_m \equiv H_m(\psi = 1)$. Continuity of the flux across the plasma-vacuum boundary, relates the vacuum coefficients B_m and L_m to the plasma coefficients D_m . Straightforward though tedious algebra obtains the energy:

$$\begin{aligned} \frac{2\delta W}{\pi} = & \alpha \left\{ -2 D_1 L_1^\alpha \right\} + \alpha^2 \left\{ -\left(\frac{21}{4}\right) D_1^2 + 4 D_1 D_3^\alpha + 4 D_1 D_5^\alpha \right. \\ & + 2 \sum_{m=1}^{\infty} (m-1) (D_m^\alpha)^2 \\ & \left. - 2 D_1 L_1^{\alpha\alpha} - 6 D_3^\alpha L_3^\alpha - 10 D_5^\alpha L_5^\alpha \right\} , \end{aligned} \quad (12)$$

and the eigenfunction:

$$\begin{aligned} \zeta_r^0 - 2\alpha r \zeta_r^\alpha = & - \left(\frac{D_1}{2}\right) \cos \theta \\ & + \alpha \left[r \cos \theta D_1^\alpha + r^3 \cos 3\theta \left(D_3^\alpha - \left(\frac{7}{4}\right) D_1\right) \right. \\ & \left. + r^5 \cos 5\theta \left(D_5^\alpha + \left(\frac{1}{4}\right) D_1\right) + \sum_{m=1,3,5}^{\infty} r^m \cos m\theta D_m^\alpha \right] \end{aligned} \quad (13a)$$

$$\begin{aligned} \zeta_\theta^0 + 2 \alpha r \zeta_\theta^\alpha = & + \left(\frac{D_1}{2}\right) \sin \theta \\ & + \alpha \left[r \sin \theta D_1^\alpha + r^3 \sin 3\theta \left(D_3^\alpha - \left(\frac{7}{4}\right) D_1\right) \right. \\ & \left. + r^5 \sin 5\theta \left(D_5^\alpha + \left(\frac{1}{4}\right) D_1\right) + \sum_{m=1,3,5}^{\infty} r^m \sin m\theta D_m^\alpha \right] . \end{aligned} \quad (13b)$$

To the order calculated, only three feedback systems contribute to the physics. By analogy with the numerical experiment reported in the previous section, we let each of them respond to the plasma motion by creating coil currents in proportion to some linear combination of perturbed flux:

$$L_m = G_m (\Delta\phi_v) . \quad (14)$$

This form can be shown to leave the stability operator self-adjoint so that an energy principle will still apply. The "gain", G_m , should be at least of order α so that the feedback system has no effect when α is zero. (A circular plasma is motionally stable). Hence $L_m^\alpha = G_m^\alpha (\Delta\phi_v^0)$. Equation (8), for ϕ_v shows that, $\Delta\phi_v^0$ is proportional to D_1 , with a constant of proportionality that depends on the location of the observation points. If we absorb the constant of proportionality into the G -symbol for the gain, the first order contribution to the energy becomes

$$\frac{2\delta W^\alpha}{\pi} = -2 G_1^\alpha (D_1)^2 \quad (15)$$

Thus, to first order in α , the system stability depends only on the sign of G_1^α . The interpretation of this result is straightforward, for we recognize that the zeroth order eigenfunction, given by Eq. (13), corresponds to a rigid shift in the $-x$ direction. To stabilize this rigid motion, we should expect to place a feedback coil on the x axis. However, we must be sure to induce current in the coil of the opposite sign to the plasma current, otherwise the effect is destabilizing.

Suppose now that $L_1^\alpha = 0$. Then δW^α vanishes, and stability is determined by the second order terms in δW . To simplify the analysis of $\delta W^{\alpha\alpha}$, we choose a feedback model that is motivated by the form of the eigenfunction without feedback: Since the zeroth order displacement eigenfunction is a rigid shift, it is appropriate to set the rigid shift component of the first order displacement equal to zero, i.e., $D_1^\alpha = 0$. Minimizing δW with respect to the D_m 's obtains $D_3^\alpha = - (1/2) D_1$, $D_5^\alpha = - (1/4) D_1$, and $D_m^\alpha = 0$ for $m \neq 3, 5$. The minimizing radial eigenfunction (first order) is therefore

$$\zeta_r^\alpha = \left(\frac{9}{8}\right) r^2 D_1 \cos 3\theta, \quad (16)$$

an $m = 3$ wrinkle superimposed on the rigid shift. [9] It makes sense, therefore, to consider the following model:

$$L_3^\alpha = L_5^\alpha = 0,$$

and

$$L_1^{\alpha\alpha} = G_{11}^{\alpha\alpha} D_1 + G_{13}^{\alpha\alpha} D_3. \quad (17)$$

This corresponds to a coil on the x axis with an ability to respond (on account of the flux measurements) to both the rigid shift and the $m = 3$ perturbations. Substituting these expressions into δW , and minimizing with respect to the D_m yields $D_3^\alpha = [-1/2 + (1/4) G_{13}^\alpha] D_1$, $D_5^\alpha = -(1/4) D_1$, and $D_m^\alpha = 0$ for $m \neq 3, 5$.

The minimum δW is

$$\frac{2\delta W}{\pi} = \alpha^2 D_1^2 \left[-\frac{27}{4} - 2G_{11}^{\alpha\alpha} + G_{13}^\alpha - (G_{13}^\alpha)^2/4 \right], \quad (18)$$

with the corresponding eigenfunction

$$\zeta_r^\alpha = D_1 r^2 \left(\frac{9}{8} - \frac{G_{13}^\alpha}{4} \right) \cos 3\theta. \quad (19)$$

The last two terms in δW are seen to be stabilizing for $0 < G_{13}^\alpha < 4$, and optimally stabilizing for $G_{13}^\alpha = 2$. For this optimal value, the mode is stabilized if $G_{11}^{\alpha\alpha} < -23/8$. This is summarized in Fig. 5, which shows the

stable and unstable boundaries in the (G_{11}^{aa}, G_{13}^a) parameter space. It is clear that for any choice of G_{13}^a , a G_{11}^{aa} can be found which stabilizes the mode. However, the converse is not true, and the choice of G_{11}^{aa} is critical. Since the actual values of the G -gains depend on the location of the observation points, we see that this result translates into a criticality for the placement of the flux pickup loops.

It is also interesting to consider the conclusions that result from restricting the instability to take the form of a rigid displacement. These indicate that the above behavior is due to the ability of the feedback systems to distort the eigenfunction: For a rigid displacement, we must choose (see Eq. (13)) $D_3^a = (7/4) D_1$, $D_5^a = -(1/4) D_1$, and $D_m^a = 0$ for $m \neq 3, 5$. Then the expression for δW becomes

$$\frac{2\delta W}{\pi} = \alpha^2 D_1^2 \left[\frac{3}{4} - 2 G_{11}^{aa} - \left(\frac{7}{2}\right) G_{13}^a \right] . \quad (20)$$

The stable and unstable regions for this rigid instability are also shown in Fig. 5. Because of the linearity of δW on the G 's, it follows that a G_{11}^{aa} can be found, to stabilize the mode, for any value of G_{13}^a . This time, the converse is also true. Therefore, for a rigid instability, the detailed placement of flux pickup loops for monitoring the motion is not critical.

4. CONCLUSIONS

We have demonstrated the usefulness of a new technique for analyzing the stability and control properties of an axisymmetric tokamak using the time-dependent simulation code TSC to perform frequency domain analysis. Using this technique, we find that in the PBX-M tokamak, certain placements of the magnetic pickup coils, on the inboard side, lead to an unstable system,

regardless of the gain, whereas other placements, on the outboard side, will give a stable system for sufficiently large values of the gain. A simplified analytical model suggests this behavior results from the non-rigid deformable nature of the plasma cross section. No such effect is present when the plasma is modeled as a current filament or as a finite size rigid conductor.

We can interpret this phenomena qualitatively in terms of a simple physical picture. As part of the plasma instability, a perturbed magnetic field is produced in the vacuum region and this is sensed by the magnetic pickup coils. If the plasma is unstable enough, it can modify its eigenfunction to deform its cross section so that a null in the perturbed vacuum magnetic field will appear at the position of the observation loops. Since these loops will then be unable to detect the plasma instability, the feedback system will be rendered inoperative.

We also emphasize the importance of the two limiting cases for stability analysis of this system. For frequencies that are large compared to the plate resistive times, we can treat the plates as perfect conductors, neglect the active feedback system, and perform standard ideal MHD analysis of the system. In the opposite limit, that of very low frequencies, the conducting plates are transparent and do not enter into the analyses. In this limit, one must consider the system consisting only of a deformable plasma and the active feedback system.

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FIGURE CAPTIONS

Fig. 1 Schematic of Modified Princeton Beta Experiment (PBX-M). For the numerical simulations, observation pairs 1 and 2 are separately used for feedback control.

Fig. 2 Block diagram for the frequency-response analysis of the control system.

Fig. 3 Top: Frequency dependence of the amplitude and phase of transfer function G when observation pairs 1 and 2 are used to monitor the flux.

Bottom: Nyquist curves resulting from the mapping to the complex G plane.

Fig. 4 Contours of constant flux for analytic model. The equilibrium magnetic field is produced by coils which push on the sides and pull at the corners. A pair of crosses on the midplane denote a typical observation pair for monitoring the position instability.

Fig. 5 Stable and unstable regions for a range of values of the gains G_{11}^{aa} and G_{13}^a .

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Fig. 1

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Fig. 2

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Fig. 3

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Fig. 4

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Fig. 5

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