Need for Novel Suppressors and Advanced Modern Control Systems for Burning Plasmas

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Motivation

- 1. Need for remote non-magnetic suppressors
  - Magnetic Suppressors like saddle coils will **not work** for internal/infernal MHD modes. Probes & electrodes not allowed in the core.
  - Explore non-magnetic suppressors:
    - Modulated neutral beams
    - Modulated electron cyclotron heating (ECH)
- 2. Need for advanced modern control systems
  - Optimal control in the presence of noise
  - Plasma parameters are time dependent

    ➔ feedback control circuit parameters must change correspondingly

    ➔ adaptive optimal control

INTRODUCTION

3. AN INTELLCTUAL BAND GAP BETWEEN CONTROL SYSTEMS SCIENCE AND PLASMA PHYSICS

- CONTROL SYSTEMS SCIENCE IS VALID FOR LUMPED PARAMETER SYSTEMS ONLY ~ SYSTEMS CHARACTERIZED BY ORDINARY DIFFERNTIAL EQS.

Highly developed and sophisticated! Vast literature!

- IT IS NOT VALID FOR DISTRIBUTED PARAMETER SYSTEMS LIKE PLASMAS ~ CHARACTERIZED BY PARTIAL DIFFERNTIAL EQS.

- NO FORMAL CONTROL THEORIES EXIST FOR P.D.E.s

- THE MOST FUNDAMENTAL HURDLE IS THE CONCEPT OF DYNAMICAL STATES.

NTH. ORDER ODE : N STATE VARIABLES

NTH. ORDER PDE : N-FOLD INFINITY OF STATES.

AS STRICTLY MATHEMATICALLY SPEAKING, EVERY PHYSICAL VARIABLE AT EVERY POINT IN SPACE IS A DYNAMICAL STATE.

4. A PHYSICALLY MOTIVATED DEFINITION OF DYNAMICAL STATES OF PLASMAS

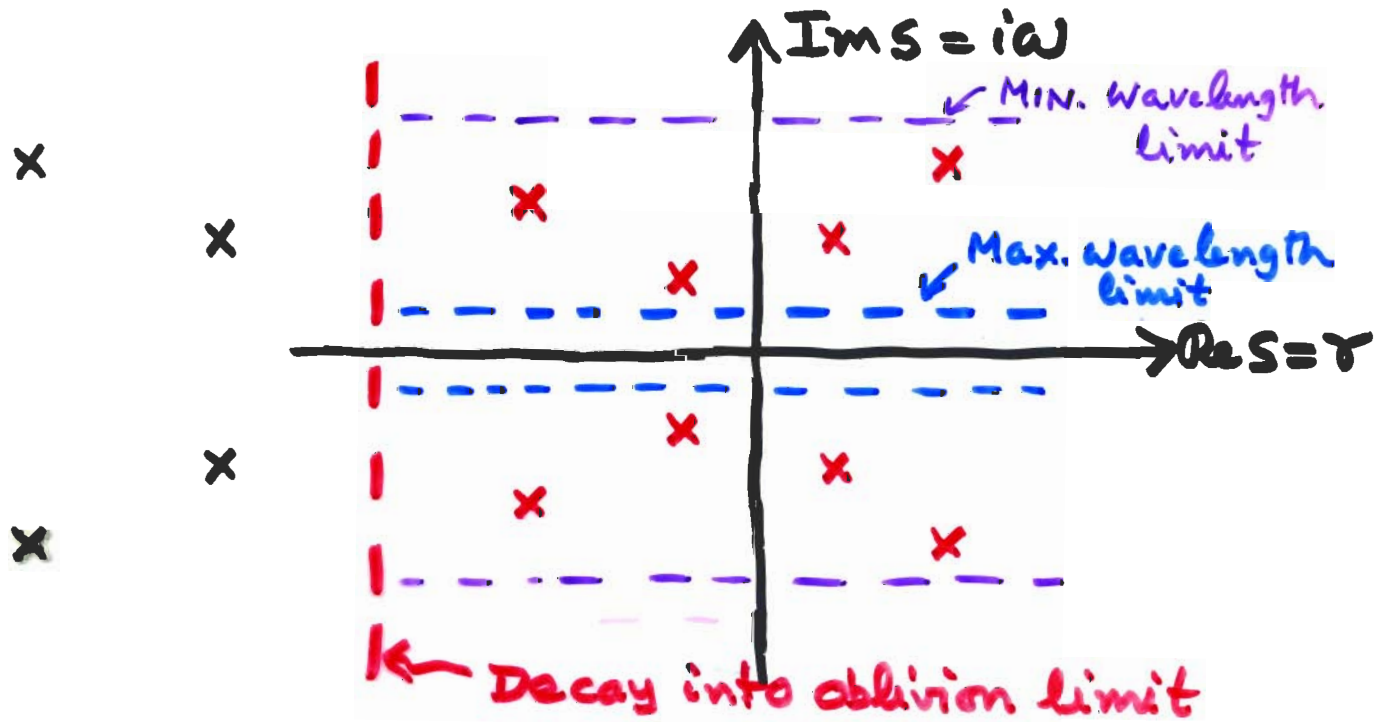
- CONSIDER A CLASS OF INSTABILITIES CHARACTERIZED BY A DISCRETE SET OF NORMAL MODES.

$\Downarrow$

- THE DYNAMICS CAN BE SUMMARIZED IN TERMS OF TEMPORAL BEHAVIOR OF THE AMPLITUDES OF THESE MODES

$\Downarrow$ ODE

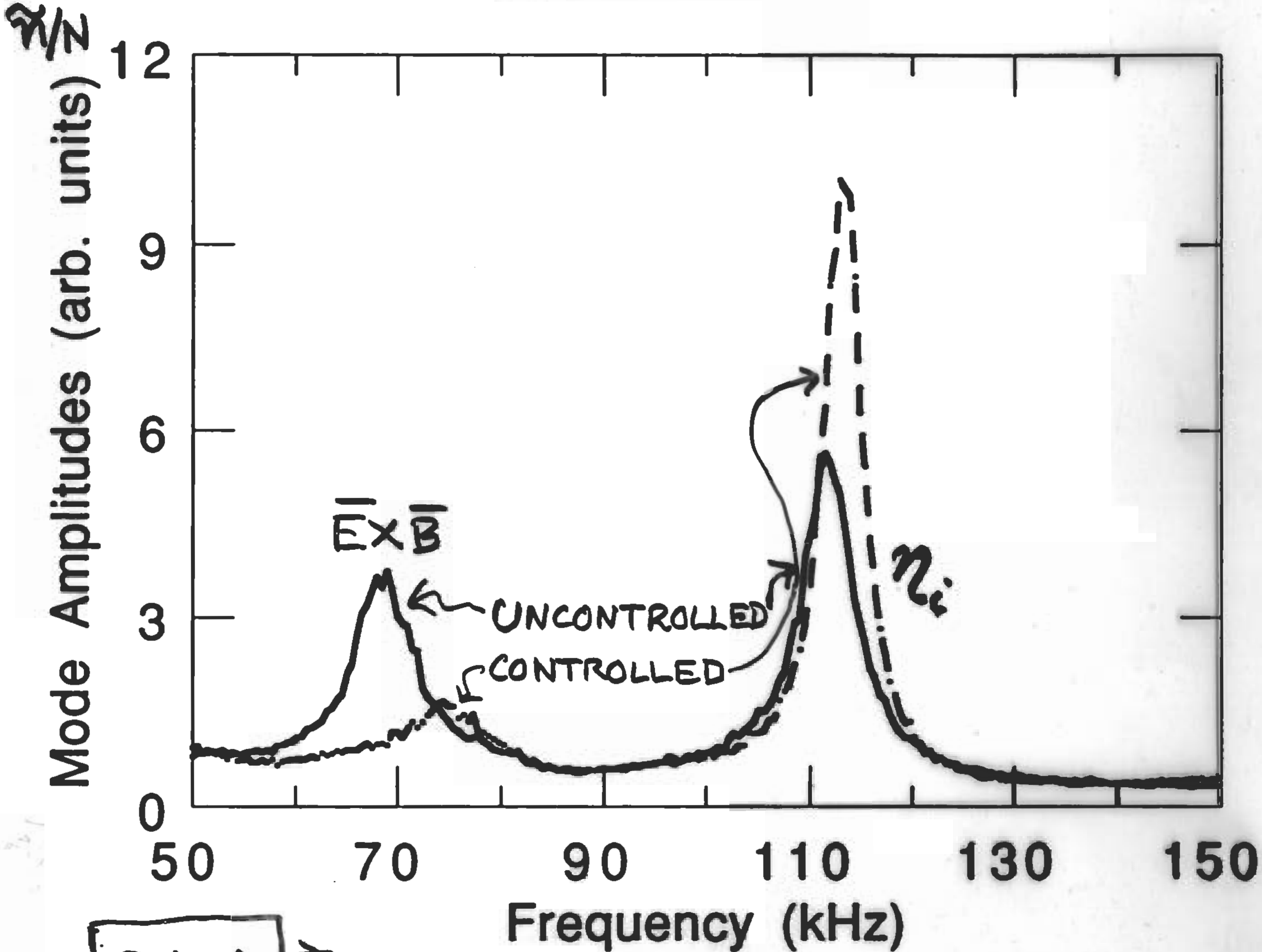
- TRUNCATE TO RETAIN THE DOMINANT POLES ONLY. CALL THIS FINITE DISCRETE SET 'NORMAL MODE STATES'.



BASIC RESEARCH ON FEEDBACK CONTROL OF PLASMA INSTABILITES IN THE COLUMBIA LINEAR MACHINE (CLM)

2. An example of Partial Suppression

SPECTRUM



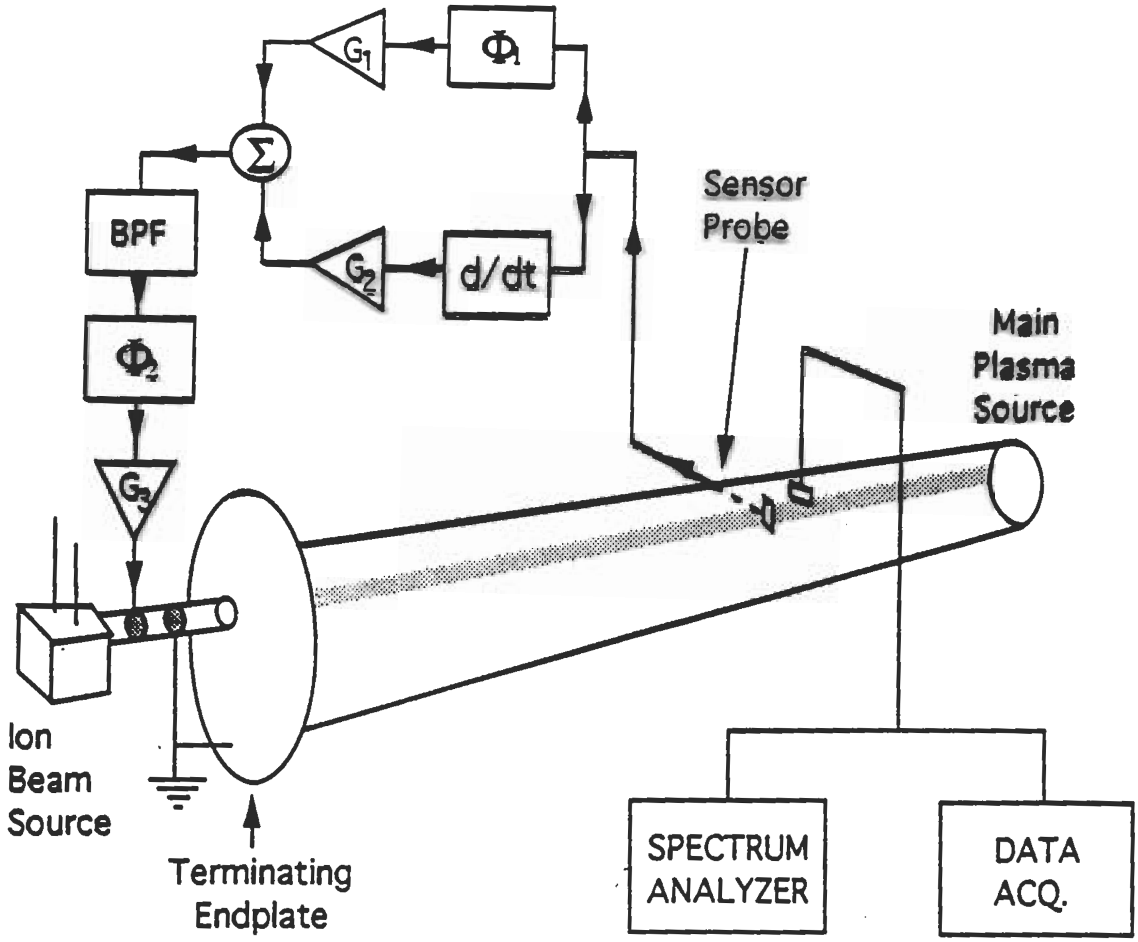


Fig. 9 Experimental Setup of Multi-mode Feedback

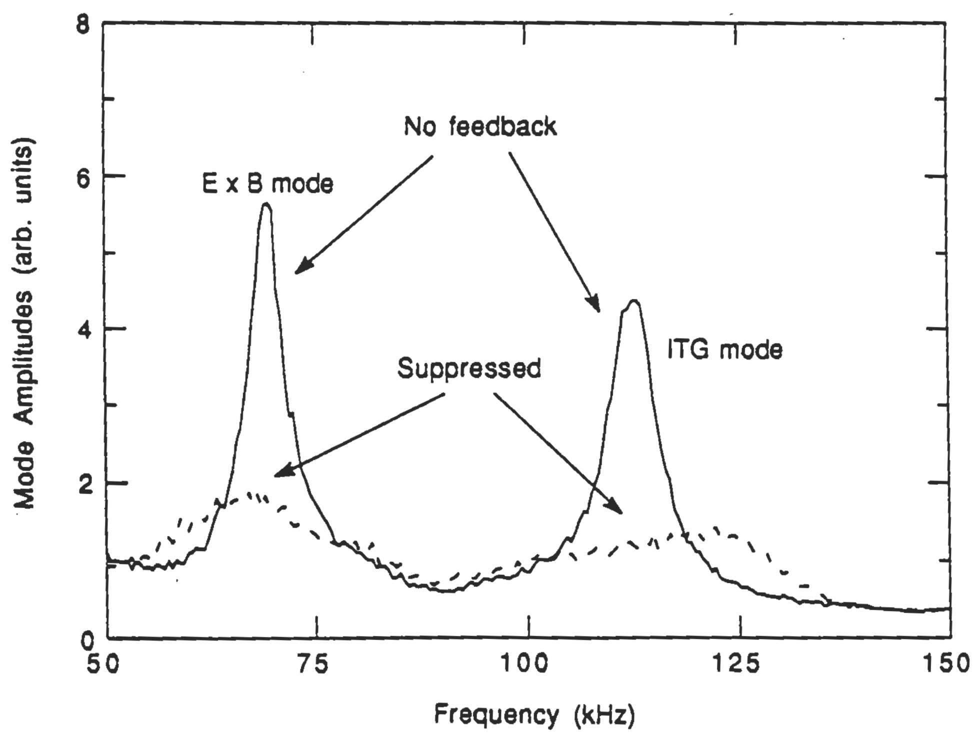


Fig. 10 Spectra of Mode Amplitude for Optimum Suppression

A THEORETICAL MODEL

Two modes with frequencies

$$s_1 = \gamma_1 + i\omega_1 \;,\quad s_2 = \gamma_2 + i\omega_2$$

can be represented in the transfer function

$$H(s) = N(s)\left\{\left[(s-\gamma_1)^2 + \omega_1^2\right]\left[(s-\gamma_2)^2 + \omega_2^2\right]\right\}^{-1}$$

With feedback the modified D.R. is

$$1 - H(s)\,G(s) = 1 - H(s)\left(k_1 + k_2 s/\omega_s\right) = 0$$

where $k_1 = k_{10}\, e^{i\phi_1(\omega)}$, $k_2 = k_{20}\, e^{i\phi_2(\omega)}$

solve for k_{10}, k_{20}, ϕ_1 & ϕ_2

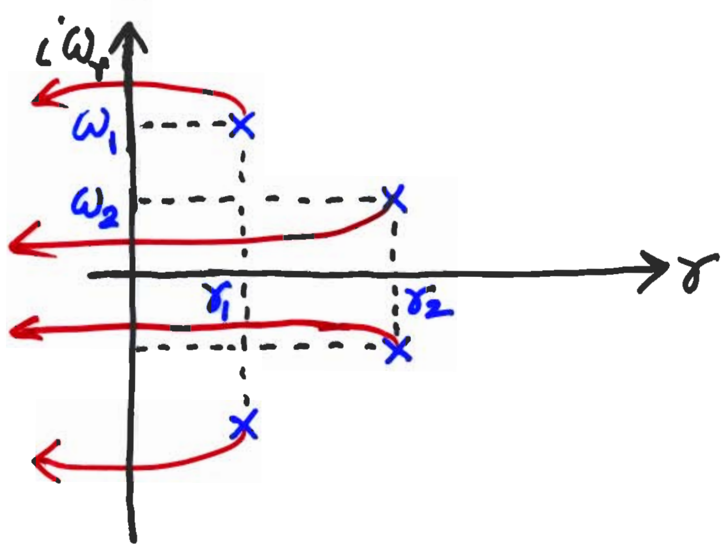
Define $G_R \equiv \left| k_{20}/k_{10} \right|$, $\phi_{1R} \equiv \phi_2(\omega_1) - \phi_1(\omega_1)$

$$\phi_{2R} \equiv \phi_2(\omega_2) - \phi_1(\omega_2)$$

Using system parameters:

$G_R \sim 3.5$, $\phi_{1R} \sim 218^\circ$, $\phi_{2R} \sim 327^\circ$ Theoretical

$\sim 3.6 \pm .2$ $\quad \sim 210^\circ \pm 15^\circ$ $\quad \sim 310^\circ \pm 15^\circ$ Experimental



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Optimal Stochastic Feedback Control of Resistive Wall Mode (RWM) in the Presence of Noise

M.Nagashima, A.K.Sen and R.Longman
Columbia University

Motivation

- Several limitations: past work
  - Only 1 unstable mode. Need for multimode stabilization
  - Past goal is only stabilization. Need control power and its minimization! Need fluctuation energy and its minimization! Need for optimal control in presence of noise!

Basic Equations of a Single RWM

- Variables: I_1 (plasma current), I_2 (wall current), I_3 (control current).

$$L_1^{eff} I_1 + M_{12} I_2 + M_{13} I_3 = \psi_n \left(\text{state noise}\right)$$
$$\gamma M_{12} I_1 + (\gamma + \tau_2^{-1}) L_2 I_2 + \gamma M_{23} I_3 = 0$$
$$\gamma M_{13} I_1 + \gamma M_{23} I_2 + (\gamma + \tau_3^{-1}) L_3 I_3 = u(\text{input})$$

- The above equations can be generalized:

$$\dot{I} = AI + Bu + D\psi_n \qquad (1)$$
$$\psi(t) = H^T I(t) + \psi_m(t) \left(measurement \quad noise \right) (2)$$

- Goal: minimize fluctuation energy and control energy, i.e., minimize

$$J = \frac{1}{T_f} \int_0^{T_f} E[I^T(t) Q I(t) + u^T(t) R u(t)] dt, T_f \to \infty \qquad (3)$$

subject to the constraint of Eq. (1).

- **Use calculus of variations**: defining a Lagrangian L

$$L(x,\dot{x}) = I^T(t)QI(t) + u^T(t)Ru(t) + \lambda^T(t)[AI(t) + Bu(t) - \dot{I}(t)]$$

where $x = (I^T\ U^T\ \lambda^T)^T$, λ is a Lagrange multiplier.

- **Then the optimal control** minimizing J of Eq. (3) satisfies the Euler-Lagrange equation:

$$\frac{d}{dt}\left(\frac{\partial L}{\partial \dot{x}}\right) - \frac{\partial L}{\partial x} = 0$$

One resulting equation is:

$$u(t) = -R^{-1}B^T\lambda(t) \qquad (4)$$

Two other resulting equations:

$$\begin{pmatrix} \dot{I}(t) \\ \dot{\lambda}(t) \end{pmatrix} = \begin{pmatrix} A & -BR^{-1}B^T \\ -Q & -A^T \end{pmatrix} \begin{pmatrix} I(t) \\ \lambda(t) \end{pmatrix}$$

- **It** can be shown that $\lambda = SI$, **where S is the** solution **of the matrix Riccati Eq:**

$SA + A^T S - SBR^{-1}B^T S = -Q$. Then from Eq. (4):

STATE FEEDBACK $\boxed{u(t) = -K_c I(t)} = -R^{-1}B^T SI(t)$ (5) ; $K_c = R^{-1}B^T S$

Note: optimal feedback is necessarily stabilizing!

- **Solution**: assume $\psi_n(t)$ is white noise, $\psi^2_{nRMS} = W$:

$$(A - BK_c)I^2_{RMS} + I^2_{RMS}(A - BK_c)^T = -DWD^T$$

Design of a State Observer (Kalman Filter)

- Sensor output: $\boxed{\psi(t)} = \underbrace{HI(t)}_{\text{Linear combination of states}} + \psi_m(t)\,(\text{measurement noise})$
- Observer Eq: $\dot{\hat{I}}(t) = A\hat{I}(t) + Bu(t) + K_f[\psi(t) - H\hat{I}(t)]$
- Determination of K_f: estimation error $e = I - \hat{I}$:

$$\dot{e}(t) = (A - K_f H)e(t) + D\psi_n(t) - K_f\psi_m(t)$$

- Minimization of $P(t) = E[e(t)e^T(t)]$ via a similar procedure of variational calculus to yield the observer Ricatti Eq:

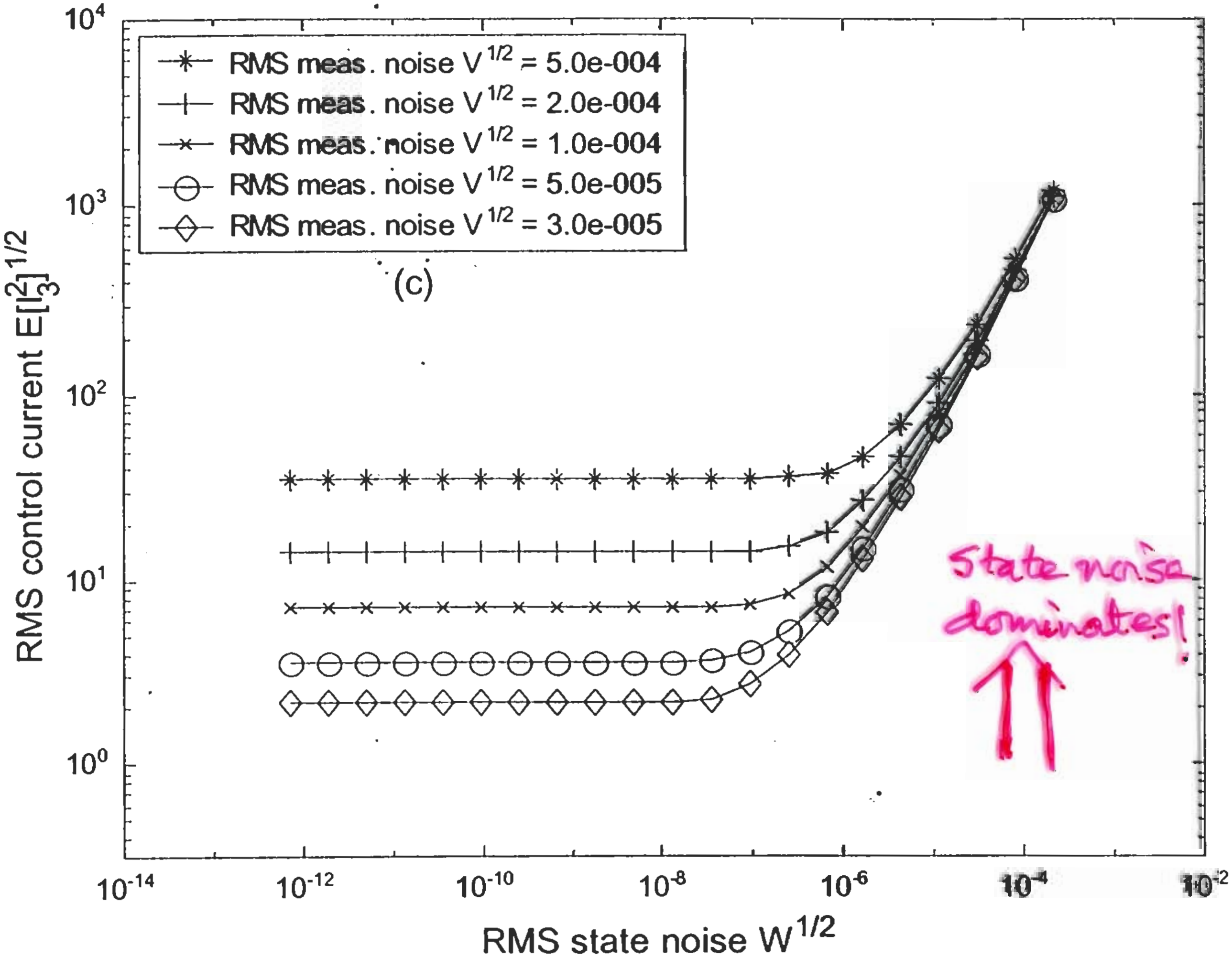
$$0 = (A - K_f H)\overline{P} + \overline{P}(A - K_f H)^T + DWD^T + K_f V K_f^T$$

$$K_f = \overline{P}H^T V^{-1}; \psi_{nRMS}^2 = V$$

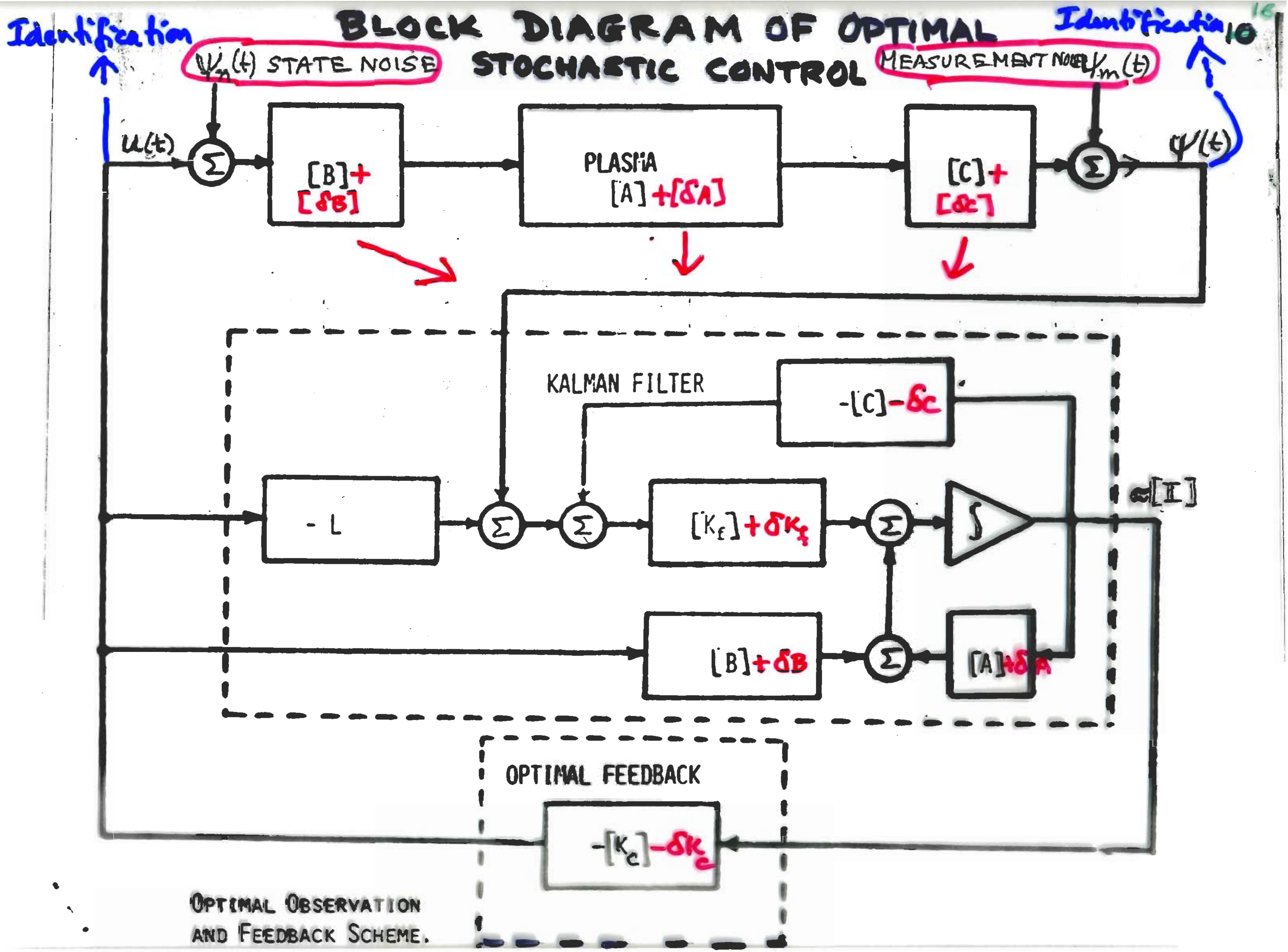
Then $\quad I_{RMS}^2 = \hat{I}_{RMS}^2 + \overline{P}, E[uu^T] = K_c \hat{I}_{RMS}^2 K_c^T$

OPTIMAL FEEDBACK OF RWM

I_e amps



BLOCK DIAGRAM OF OPTIMAL STOCHASTIC CONTROL



OPTIMAL OBSERVATION AND FEEDBACK SCHEME.

Adaptive Optimal Control of Resistive Wall Mode(RWM)

Z.Sun, A.K.Sen, R.Longman

- System identification (determination of a plasma dynamic model)
- System identification of a system evolving in time
- Optimal stochastic control system based on the above

State Space Model:

The nominal system is a single mode RWM in the presence of plasma noise:

$$\dot{I}(t) = AI(t) + Bu(t) + D\psi_n(t)$$

$$\psi(t) = HI(t) + \psi_m(t) \qquad \textbf{(1)}$$

$$I^T = [I_1 \ \ I_2]$$

The system matrices A, B, D and H for DIII-D like parameters are:

$$A = \begin{pmatrix} -0.474 & -502 \\ -14.7 & 79.0 \end{pmatrix} \qquad B = \begin{pmatrix} -531 \\ -16500 \end{pmatrix}$$

$$D = \begin{pmatrix} -2.67\times10^8 \\ +2.23\times10^8 \end{pmatrix} \quad H^T = \begin{pmatrix} 0.650\times10^{-4} \\ 0.940\times10^{-4} \end{pmatrix}$$

The assumption about ψ_n, plant noise and ψ_m, measurement noise, is:

$$\Psi_{nRMS}=10^{-5}\text{W} \qquad \Psi_{mRMS}=2\times10^{-4}\text{W}$$

The quadratic cost function to be minimized:

$$J(t_f) = \int_0^{t_f} [I^T(t)QI(t) + u^T(t)Ru(t)]dt$$

Where the weight matrices are:

$$Q = \begin{pmatrix} 0.600 & 1.080 \\ 1.080 & 14.647 \end{pmatrix} \qquad R = 1$$

System Model

Transfer Function Model:

$$H(s) = \frac{-1.586\,s + 541.1}{s^2 - 78.53\,s - 7417} \tag{2}$$

The poles of the model are [-55, 133].

For numerical solution with Matlab, the system is discretized with a sampling period of 50 μsec. Eq.2 can be written in discrete time form as:

$$\boxed{\psi(k) + a_1\psi(k-1) + a_2\psi(k-2) = b_1 u(k-1) + b_2 u(k-2) \quad (3)}$$

where a_1=-2.004, a_2=1.004, b_1=-7.9*10^{-5}, b_2=8.0*10^{-5}.

Parameter vector

System Identification

Least Square Batch Method

Assume that the sequence of inputs {u(1), … u(k), …, u(n)} has been applied to the system and the corresponding sequence of outputs {ψ(1), …ψ (k), …, ψ (n)}has been observed. Use the unknown parameter vector $\theta^T = (a_1 \quad a_2 \quad b_1 \quad b_2)$ and the known regression vector $\varphi^T(k-1) = (-\psi(k-1) \quad -\psi(k-2) \quad u(k-1) \quad u(k-2))$.

This kind of model is called an autoregressive model.

The model can formally be written as

$$\psi(k) = \varphi^T(k-1)\theta \qquad (4)$$

Regression vector

parameter vector

Using the notation

$$\Phi = \begin{pmatrix} \vdots \\ \varphi^T(k) \\ \vdots \\ \varphi^T(n-1) \end{pmatrix} \qquad \Psi = \begin{pmatrix} \vdots \\ \psi(k+1) \\ \vdots \\ \psi(n) \end{pmatrix}$$

Eq. 4 becomes: $\Psi = \Phi\theta$ ← parameter vector (5)

output vector → ← Regression vector

The parameters θ should be chosen to minimize the least-square cost function

$$V(\theta,t) = \frac{1}{2}\sum_{k=1}^{n}\left(\psi(k) - \hat{\psi}(k)\right)^2 \tag{6}$$

If the matrix $\Phi^T\Phi$ is nonsingular, the minimum is unique and given by

$$\boxed{\hat{\theta} = \left(\Phi^T\Phi\right)^{-1}\Phi^T\Psi} \tag{7}$$

provided $(\Phi^T\Phi)^{-1}$ exists, otherwise should be replaced by $\Phi^+\Psi$.

With batch method, the identified model (RMS) of the above system is given in Fig. 1.

The convergence time is 16 ms.

Least Square Recursive Method

In adaptive controllers the observations are obtained sequentially in time. It is then desirable to make the computation recursively to save time. First, define the covariance matrix P

$$P(t) = \left(\Phi^T(t)\Phi(t)\right)^{-1} = \left(\sum_{k=1}^{n} \varphi(k)\varphi^T(k)\right)^{-1}$$

Using some matrix manipulations, the recursive least square estimation for constant system parameters takes the form

$$\hat{\theta}(k) = \hat{\theta}(k-1) + \overset{\text{weighting}}{\kappa(k)}\overbrace{(\psi(k) - \varphi^T(k)\hat{\theta}(k-1))}^{\text{correction}}$$

$$\kappa(k) = P(k)\varphi(k) = P(k-1)\varphi(k)(I + \varphi^T(k)P(k-1)\varphi(k))^{-1} \quad (8)$$

$$P(k) = (I - \kappa(k)\varphi^T(k))P(k-1)$$

In our case plasma parameters evolve in time. One method to estimate the time-varying parameters is to define a forgetting factor λ, 0 < λ ≤ 1. The most recent data is given unit weight, but data that is n

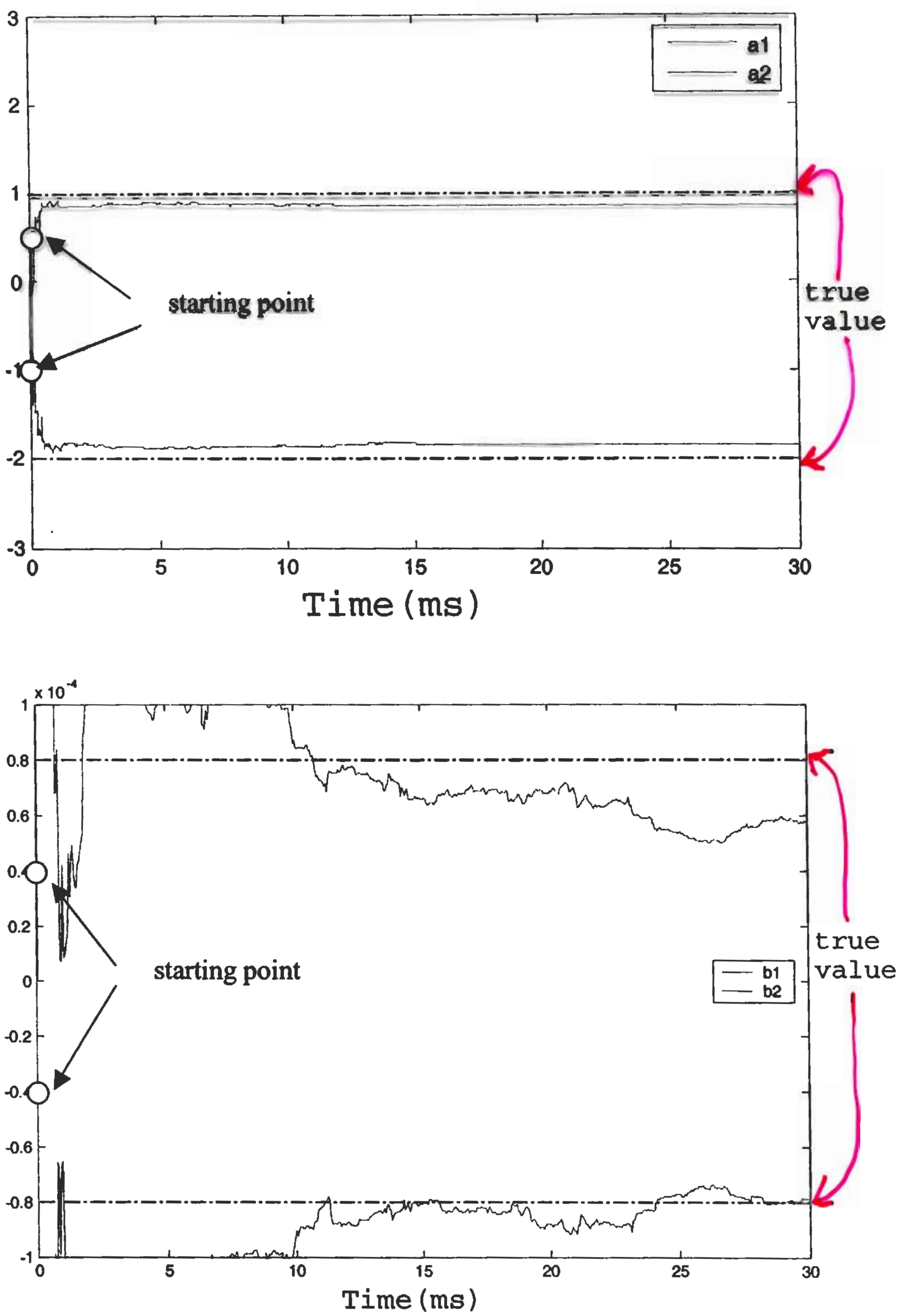


Fig. 2 System identification with recursive method.

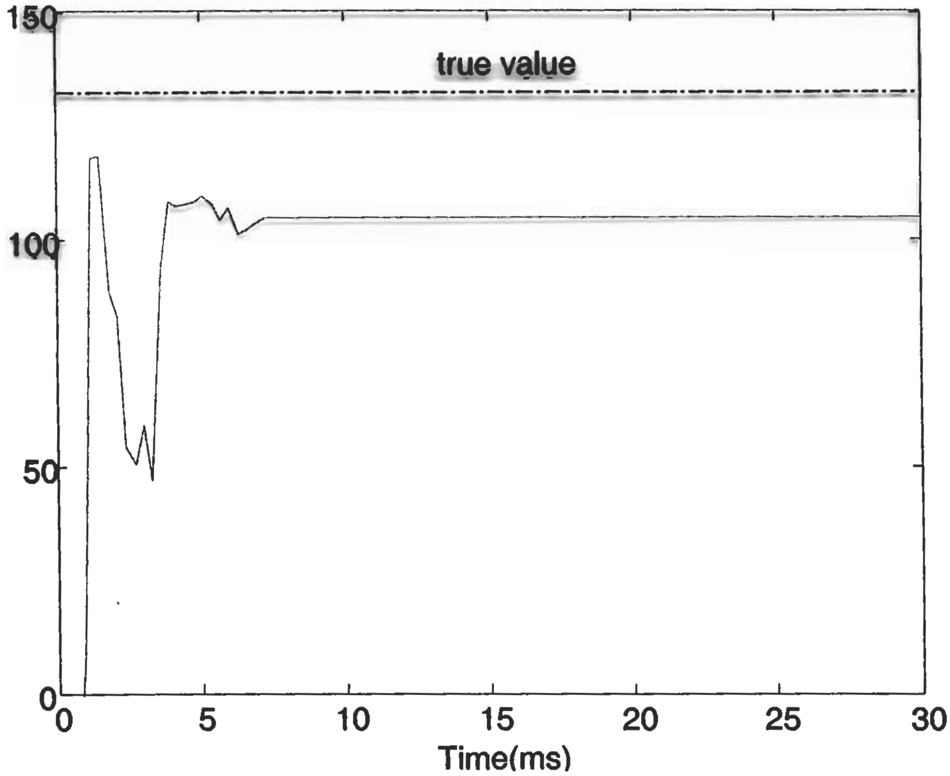


Fig. 3 Time history of identified unstable pole.

Control Response with Identified Model

Identification → Kalman filter → system states → feedback → outputs in Fig. 4.

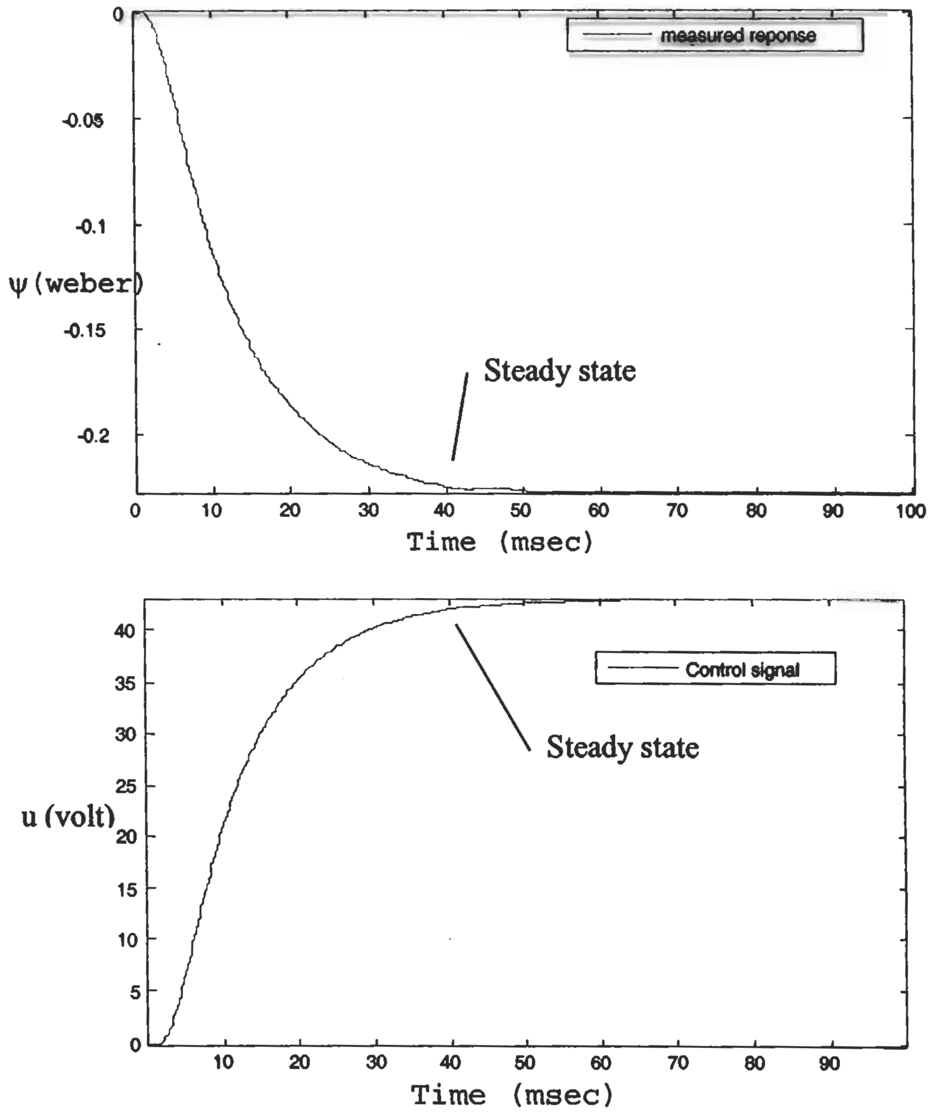


Fig. 4 Control input and stabilized system response.

A Simple Fully Adaptive System

Variation of system parameters in 150 msec (between 300ms and 450 ms).

$$A = \begin{pmatrix} -0.474 & -502 \\ -147 & 79.0 \end{pmatrix} \rightarrow A = \begin{pmatrix} -4.74 & -5020 \\ -147 & 790 \end{pmatrix}$$

The poles of the system become

[-55,135] → [-550, 1350].

System identification results are shown in Fig. 5.

The time history of the identified unstable pole is shown in Fig. 6.

The identified model is used to generate the feedback control signal series, which is shown in Fig. 7.

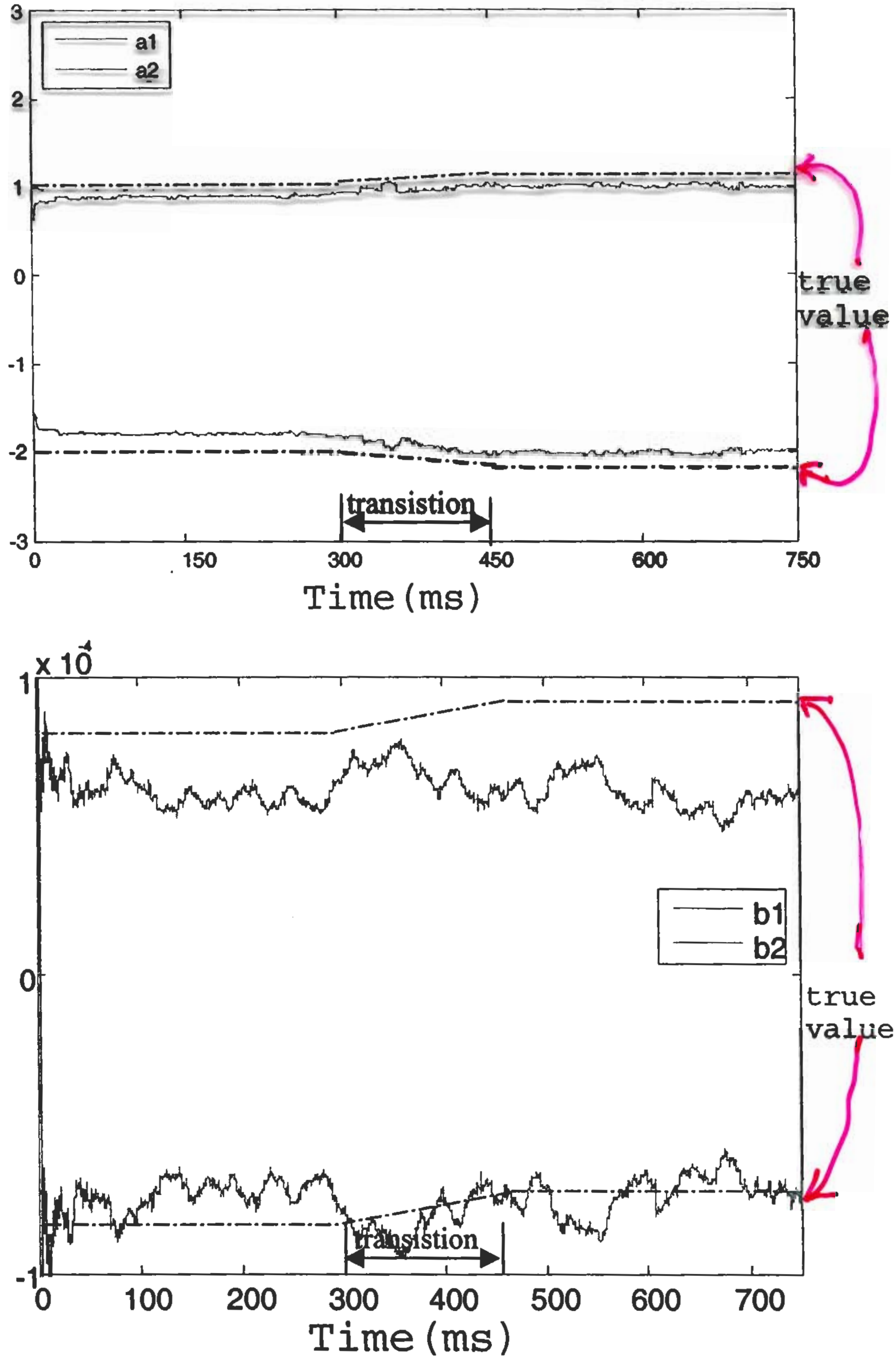


Fig. 5 System identification with recursive method for the time evolving system.

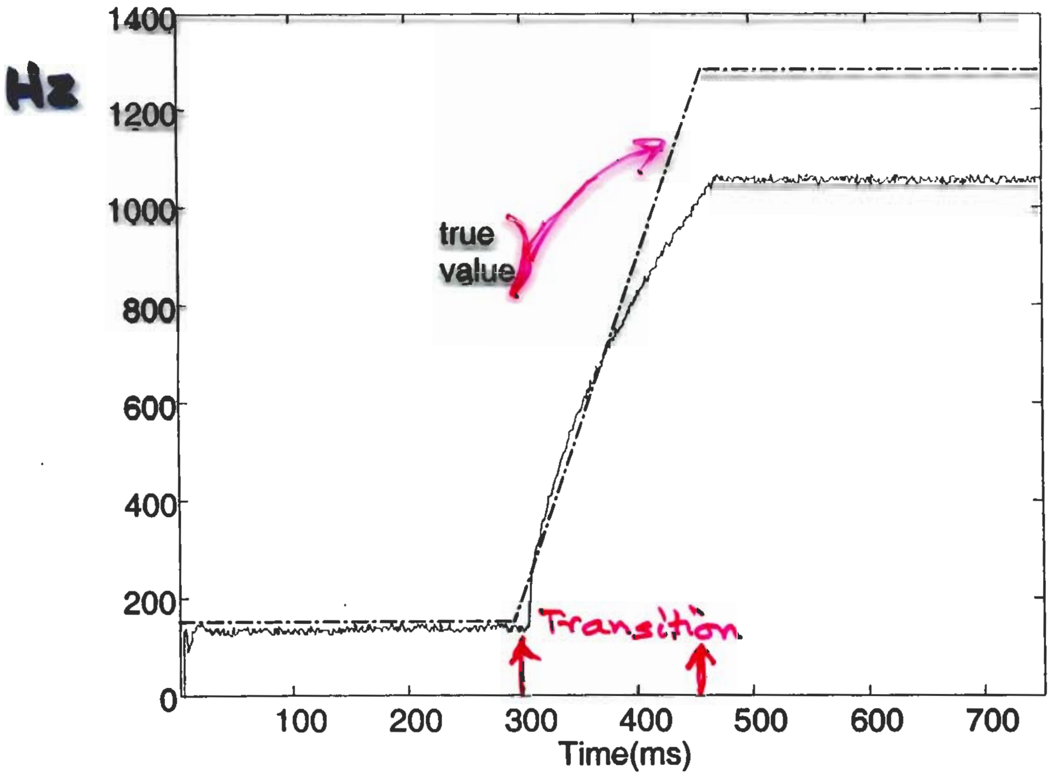


Fig. 6 Time history of identified unstable pole for the time evolving system.

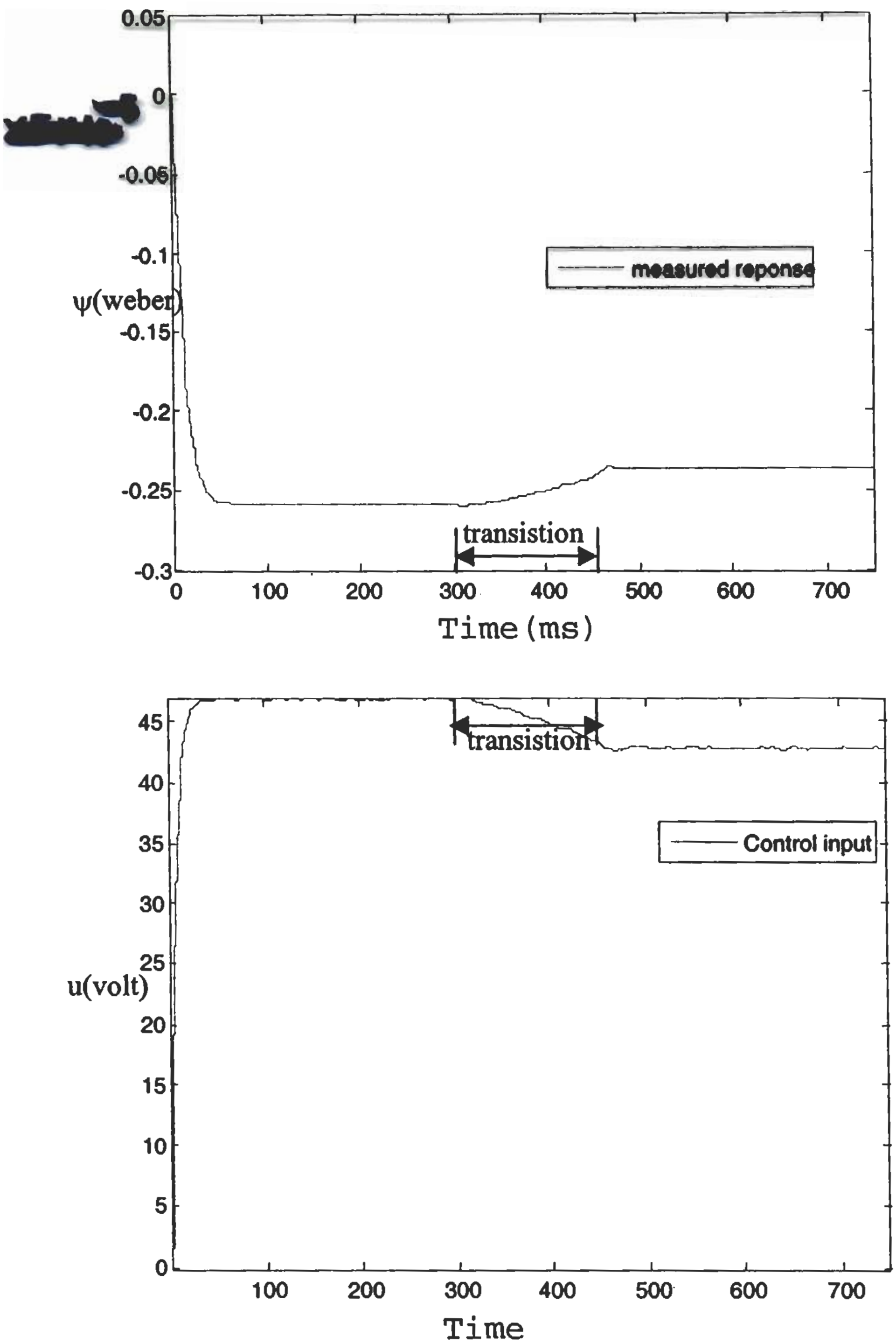


Fig. 7 Control input and stabilized system response for time evolving system.

Direct Experimental Determination of Dynamical Models of Plasma Fluctuations (Instabilities)

J.S.Chiu and A.K.Sen

Motivation

- Critical need for direct experimental measurement of plasma dynamical models: for better feedback controller design and transport understanding.
- Need for validation of current nonlinear models

➢ We attack the above problems via diagnostic use of feedback!

FEEDBACK DIAGNOSTIC:

DETERMINATION OF A NONLINEAR DYNAMIC MODEL

J. S. CHIU, A. K. SEN

METHODOLOGY

(i) Method of Ritz, Powers and Bengston

We start with a generic three wave coupling model and apply the method by Ritz, Powers and Bengston [Ch. P. Ritz et. al., Phys. Fluids B1, 153 (1989)]

$$\frac{\partial\phi(k,t)}{\partial t} = \boxed{(\gamma_k + i\omega_k)}\phi(k,t) + \frac{1}{2}\sum_{k=k_1+k_2} \boxed{\Lambda_k^Q(k_1,k_2)}\phi(k_1,t)\phi(k_2,t)$$

In discrete time using difference approach:

$$\phi(k,t+\tau) = \frac{(\gamma_k + i\omega_k)\tau + 1 - i[\Theta(k,t+\tau) - \Theta(k,t)]}{e^{-i[\Theta(k,t+\tau)-\Theta(k,t)]}}\phi(k,t) + \frac{1}{2}\sum_{k=k_1+k_2} \frac{\Lambda_k^Q(k_1,k_2)\tau}{e^{-i[\Theta(k,t+\tau)-\Theta(k,t)]}}\phi(k_1,t)\phi(k_2,t)$$

Then, in the frequency domain, multiplying by Φ_ω^* and $\Phi_{\omega_1}^*\Phi_{\omega_2}^*$ and ensemble averaging gives

$$\langle \Phi_\omega(\tau)\Phi_\omega^*\rangle = \boxed{L_\omega}\langle \Phi_\omega \Phi_\omega^*\rangle + \frac{1}{2}\sum_{\omega_2=\omega+\omega_1} \boxed{Q_{\omega_1,\omega_2}}\langle \Phi_{\omega_1}\Phi_{\omega_2}\Phi_\omega^*\rangle;$$

$$\langle \Phi_\omega(\tau)\Phi_{\omega_1'}^*\Phi_{\omega_2'}^*\rangle = \boxed{L_\omega}\langle \Phi_\omega \Phi_{\omega_1'}^*\Phi_{\omega_2'}^*\rangle + \frac{1}{2}\sum \boxed{Q_{\omega_1,\omega_2}}\langle \Phi_{\omega_1}\Phi_{\omega_2}\Phi_{\omega_1'}^*\Phi_{\omega_2'}^*\rangle$$ INTRACTABLE?

from which $L_\omega = \frac{(\gamma_k+i\omega_k)\tau+1-i[\Theta(k,t+\tau)-\Theta(k,t)]}{e^{-i[\Theta(k,t+\tau)-\Theta(k,t)]}}$ and $Q_{\omega_1,\omega_2} = \frac{\Lambda_k^Q(k_1,k_2)\tau}{e^{-i[\Theta(k,t+\tau)-\Theta(k,t)]}}$ can be solved for.

(ii) New Method via Feedback

However, due to the difficulty of calculating the fourth order moments, we use feedback with complex gain G_i to substitute for the second equation as follows:

$$\langle\Phi_\omega(\tau)\Phi_\omega^*\rangle' = (L_\omega + \frac{\boxed{G_i}}{e^{-i[\Theta(k,t+\tau)-\Theta(k,t)]}})\langle\Phi_\omega\Phi_\omega^*\rangle' + \frac{1}{2}\sum Q_{\omega_1,\omega_2}\langle\Phi_{\omega_1}\Phi_{\omega_2}\Phi_\omega^*\rangle'$$

EXPTS. DONE WITH MANY $G_i = G_1, G_2, --; i \gg 2$

TO GENERATE ARBITRARILY LARGE NO. OF EQS.

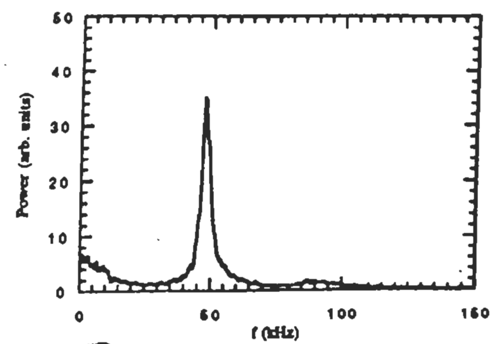
$\Downarrow$

USE SVD

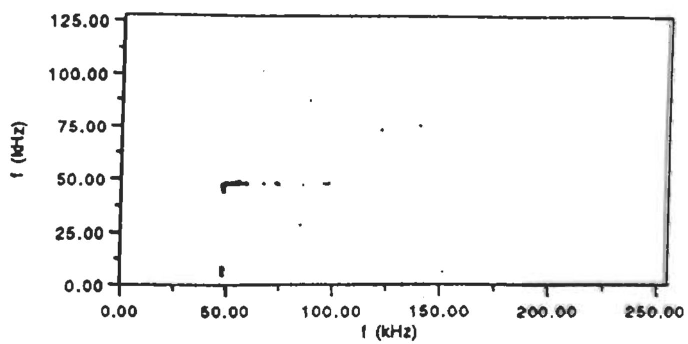
$\Downarrow$

RELIABLE RESULTS!

APPLICATION TO AN $\overline{E}\times\overline{B}$ ROTATIONAL FLUTE MODE

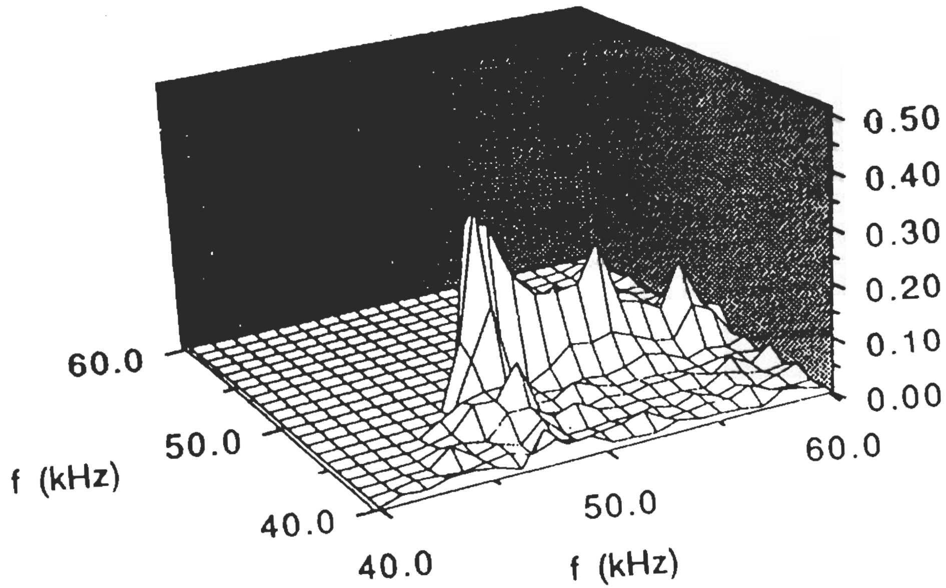


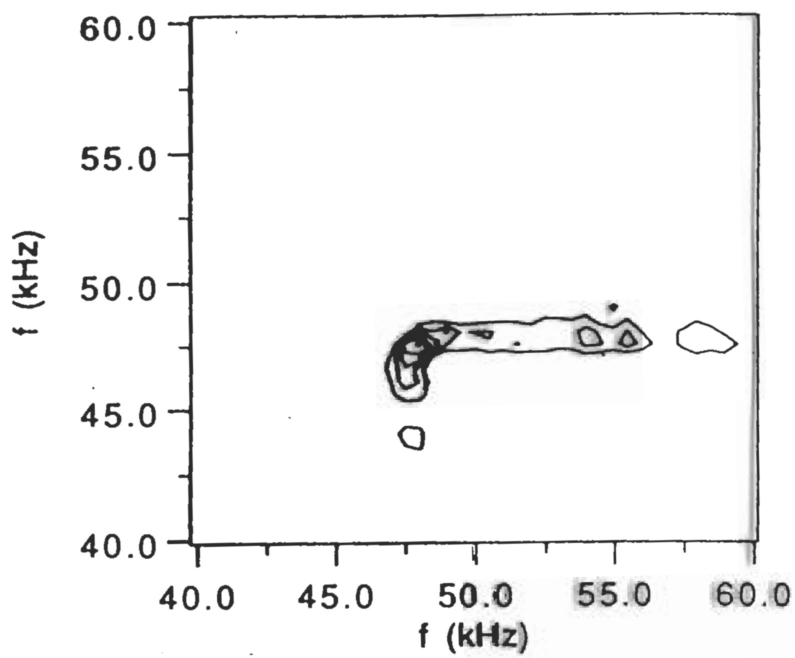
POWER SPECTRUM



BI-COHERENCE

CLOSE UP OF THE BI-COHERENCE OF THE MAIN MODE





RESULTS

MODE	REAL FREQ, KHz	GROWTH RATE, KHz	N.L. COUPLING COEFF, $(VS)^{-1} \times 10^{-2}$
K	47	2.1	$\Lambda_K = 5.6 + i1.6$
K_1	52	-2.4	$\Lambda_{K_1} = -28 + i9.4$
K_2	96	-16.5	$\Lambda_{K_2} = 1.5 + i2.7$

?

REMOTE Non-magnetic Suppressors

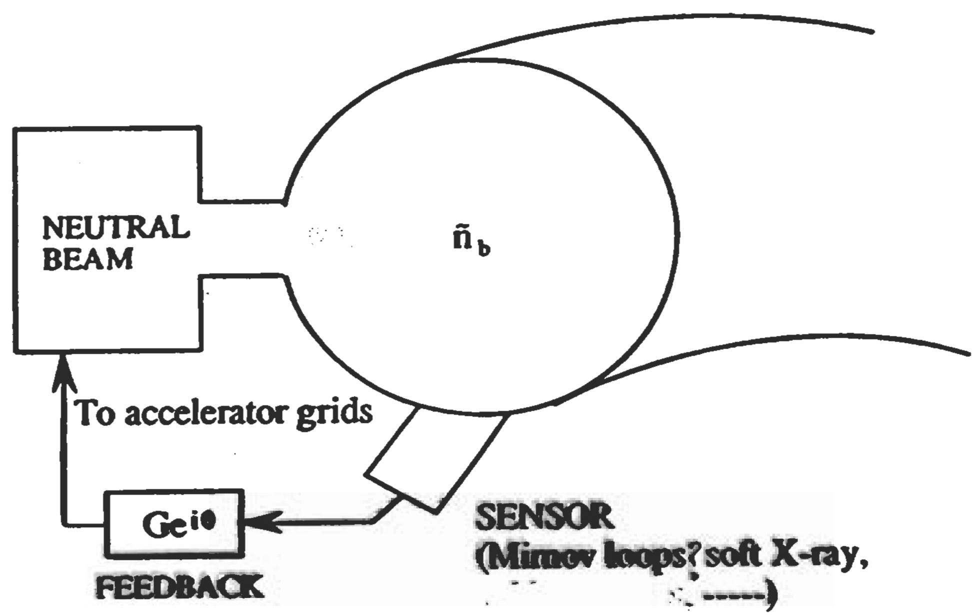
A.K.Sen

- Modulated neutral beams
- Modulated ECH

A Modulated Neutral Beam Suppressor for Internal/Infernal MHD Modes

THE BASIC IDEA

- A critical ingredient of internal/infernal modes: $(\vec{J}\times\vec{B})_r$, $(\nabla p)_r$
- A suitable control variable: Radial Momentum input via neutral beams for MHD modes
  Ion density input for ES modes



A schematic of the feedback system for the control of kink modes.

The linearized MHD eq^n with feedback:

$$\rho \frac{\partial^2 \vec{\xi}}{\partial t^2} = \vec{F}(\vec{\xi}) + \hat{e}_r M_r \qquad (1)$$

f.b.

where $M_r = m_b(\sigma_e + \sigma_i + \sigma_x) N_o V_b^2 n_b$. & $\vec{F}(\vec{\xi})$ is MHD force operator

Assuming a feedback law: $n_b/N_0 = G(\xi_r/a_0)$

Then, $M_r = d\rho G \xi_r$, $\quad d = N_0(\sigma_e + \sigma_x + \sigma_i) V_b^2 / a_0$

Taking dot product of Eq(1) with $\vec{\xi}^*$ & integrating, and extending to include vacuum & surface contributions,

$$\omega^2 + dG = \frac{\delta W_F(\vec{\xi}^*, \vec{\xi}) + \delta W_V + \delta W_S}{\frac{1}{2}\int \rho |\xi|^2 dV} = -\gamma_0^2 \qquad (2)$$

f.b.

Linear growth rate

For marginal stability: $\quad G \simeq -|G|$ and $|G| \simeq \gamma_0^2 / d \qquad (3)$

Geometrical coupling coefficient c_0:

$$C_0 \sim (L_t L_p / 4\pi^2 R a_0)\,\mathfrak{K} \sim 10^{-3}$$

$$|G|_{actual} \sim |G|\, c_0^{-1}$$

For TFTR like parameters and two beams (derated to 30 keV) & $L_p \sim 20$ cm $\times$ $L_t \sim 80$ cm each:

$$|n_b/N_0| = |G|_{actual}(\xi_r/a) \sim |G|_{actual}(B_\theta/B_{\theta 0}) \sim 2\times 10^{-5}$$

For detectable level of $(B_\theta/B_{\theta 0}) \sim 10^{-3}$.

$$(I_b)_{total} \sim 53\text{A}, \qquad (P_b)_{total} \sim 1.6\ \text{MW}$$

FOR PBX-M (FSX) LIKE PARAMETERS AND ONE BEAM WITH $E_b \sim 30$ keV; $L_p \sim 22$ cm $\times$ $L_t \sim 33$

$$|n_b/N_0| \sim |G|_{actual}(B_\theta/B_{\theta 0}) \sim 2\times 10^{-5}$$

FOR DETECTABLE LEVEL OF $B_\theta/B_{\theta 0} \sim 10^{-3}$

$I_b \sim 10$ A, $P_b \sim .3$ MW

NOTE: EXISTING BEAM FOR PBX-M

$E_b \sim 40$ to 45 keV, $I_b \sim 20$ to 30A

Modulated ECH Feedback for Internal and Infernal Modes

- Consider purely radial ECH injection: the transverse energy of electrons: $W_{e\perp} \sim \langle p_{e\perp} \rangle$ will nearly instantaneously (compared to γ, ω_r) increase with resonance response! $P^{ECH} = P_0^{ECH}(1+\alpha e^{-i\omega_r t})$.

- A naïve model of the instability:

$$\rho_0 \frac{d^2\overline{\xi}}{d^2 t} = -\nabla\tilde{p} + \widetilde{\mathrm{J}\times\mathrm{B}}\left(\overline{\xi} = \text{plasma displacement}\right) \approx \rho_0\gamma_0^2\overline{\xi} - \nabla\tilde{p}_{e\perp}^{f.b.} \quad \text{(models the growth rate)}$$

set $\tilde{p}_{e\perp}^{f.b.} = G\xi$, $\nabla \sim L_{dep}^{-1}$, and find:

$$-\omega^2 = \gamma_0^2 - G/\left(\rho_0 L_{dep}\right) \qquad (3)$$

$\therefore$ Marginal stability, if $G = \gamma_0^2 L_{dep} \rho_0$ (4)

Using Eqs (1), (3) and (4): $P_0^{ECH} \sim \nu_d \rho_0 \gamma_0^2 L_{dep} \xi / \alpha$; $\nu_d = \textit{diffusion rate}$ (5)

Coupling coefficient C: $C \approx (\text{Radial Conv.})(m/2\pi a)(n/2\pi R)$ (6)

For a medium size tokamak:

$\gamma_0 \sim 10^4$, $\nu_d \sim 10^3$, $\xi = 10^{-2}$, $L_{dep} \sim (2 \text{ to } 4)\times 10^{-2}$, $\alpha \sim 1$, beam spot size: Diam $(2 \text{ to } 4)\times 10^{-2}$

- From Eqs. (5) and (6):

$$P_0^{ECH} \sim 5 \text{ to } 10 \text{ MW feasible!}$$

Suggestion: try a simple open loop test to check viability; turning ECH on and off, look for magnetic or soft X-ray signature for plasma displacement.

Conclusions

- In principle, all plasma instabilities with discrete spectra can be feedback stabilized (observability and controllability); demonstrated theoretically and experimentally.
- For instabilities in the deep interior of the magnetic fusion devices, one may consider modulated NB or RF(ECH) suppressors.
- Adaptive (optimal) control appears to be feasible for slow growing modes. It is a must for future magnetic fusion machines.