Plasma Response Control Using Advanced Feedback Techniques

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Summary

- ITER steady-state scenarios will require resistive wall mode (RWM) feedback
- Linear Quadratic Gaussian (LQG) control techniques are applicable to ITER’s internal and external coils
  - LQG offers noise and disturbance rejection
  - Use of both $B_p$ and $B_r$ sensors
- DIII-D experiments and simulations show promising results with external coils and LQG control
• PID control directly uses measurements to calculate feedback

measurements → controller → feedback
LQG Control Uses a System Model to Enable Noise Rejection

- PID control directly uses measurements to calculate feedback

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measurements ➔ controller ➔ feedback
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- LQG control requires a physics model
  - VALEN models the RWM and its interaction with the vacuum vessel and coils
- Physics model and knowledge of noise distribution allows filtering of Gaussian noise from measurements
  - More commonly known as Kalman filtering

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measurements ➔ Kalman filter ➔ controller ➔ feedback

VALEN
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DIII-D
NATIONAL FUSION FACILITY

1711-0139 / 4

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External Coils Provide Feedback Suppression

- DIII-D is equipped with both internal (\textit{I-coils}) and external (\textit{C-coils}) control coils
Internal Coils Drive Perturbation

- I-coils are powered in $n=1, 240^\circ$ quartets
  - Pitch angle between upper and lower coils maximizes coupling to kink structure
External Coils Provide Feedback Suppression

- C-coils are powered in $n=1, 180^\circ$ pairs
  - Feedback algorithm may be either PID or LQG using voltage control power supplies
\[ \beta_n < \text{no-wall limit} \]

stable

\[ J \times B = \nabla P \]

MHD equilibrium

design LQG controllers here

L-coils
C-coils
\[ J \times B = \nabla P \]

**MHD equilibrium**

\[ \beta_N < \text{no-wall limit} \]

**stable**

- L-coils
- C-coils

**operate here with LQG control**

\[ J \times B = \nabla P \]

**MHD equilibrium**

\[ \beta_N > \text{no-wall limit} \]

**unstable**

**design LQG controllers here**
I-coils Excite a Stable MHD Mode to Finite Amplitude

- In open loop, this technique is called MHD spectroscopy
- Plasma response will be greatest when rotation is in same direction as $I_p$
I-coil Frequency is Varied for Each Perturbation, Drives a Corresponding Plasma Response

- H-mode target discharge has many ELMs
  - LQG controller can filter these out
- Negative frequency indicates perturbation rotates counter to $I_p$
I-coil Frequency is Varied for Each Perturbation, Drives a Corresponding Plasma Response

• H-mode target discharge has many ELMs
  – LQG controller can filter these out
• Negative frequency indicates perturbation rotates counter to $I_p$

![Graph showing I-coil current, B_p sensor, and C-coil current over time](image)
Normalized Plasma Response ($G/k\text{A}$) Determines Effectiveness of Feedback Algorithms

- Identifies the plasma response at the perturbation frequency
- Normalized plasma response = $1.53 \, G/0.58 \, k\text{A} = 2.61 \, G/k\text{A}$
• Data points filtered on time averaged $<\beta_n/li>$
  - Ensures similar discharges are compared
• Open loop perturbations
Open Loop Response Agrees With Experiment Simulations Using VALEN

- Data points filtered on time averaged \(<\beta_N/\ell_i>\)
  - Ensures similar discharges are compared
- Open loop perturbations
- Open loop simulation
• Data points filtered on time averaged $<\beta_N/\ell_i>$
  – Ensures similar discharges are compared
• Open loop perturbations
• Open loop simulation
• Closed loop perturbations

Closed Loop Response Agrees With Experiment Simulations Using VALEN

![Graph showing normalized plasma response with perturbation frequency](image-url)
Closed Loop Response Agrees With Experiment Simulations Using VALEN

- Data points filtered on time averaged $<\beta_N/\ell_i>$
  - Ensures similar discharges are compared
- Open loop perturbations
- Open loop simulation
- Closed loop perturbations
- Closed loop simulation
I-coil or C-coil Feedback Has Helped AT Discharges Access Higher $\beta_N$ After Failing Without Feedback

- Equilibrium reconstructed parameters of AT discharge
- C-coil feedback as effective as internal coils
C-coil Feedback Nearly Reproduces Performance of a DIII-D Steady State AT Discharge

• Comparable $\beta_N$ and energy confinement time achieved during flattop
Conclusions

• C-coil LQG feedback is as effective as I-coil feedback using proportional gain only

• LQG can optimize effectiveness of ITER’s internal coils

• These techniques are promising for external coils on DEMO

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VALEN Models the RWM and its Interaction with Surrounding Conductors

- Finite element code of coupled circuit equations
- RWM is represented as a current on the plasma surface
- Provides linear model for LQG controller

\[
\begin{bmatrix}
L_{ww} & L_{w_f} & L_{wp} \\
L_{f_w} & L_{f_f} & L_{f_p}
\end{bmatrix}
\frac{d}{dt} \begin{bmatrix} I_w \\ I_f \\ I_d \end{bmatrix} = - \begin{bmatrix} R_w & 0 & 0 \\
0 & R_f & 0 \\
0 & 0 & R_p \end{bmatrix} \begin{bmatrix} I_w \\ I_f \\ I_d \end{bmatrix} + \begin{bmatrix} 0 \\ V_f \\ 0 \end{bmatrix}
\]

User defines torque and stability parameters

\[ \begin{bmatrix} S \end{bmatrix} \begin{bmatrix} \alpha \end{bmatrix} \]

VALEN outputs three matrices: L, R and M which are part of the above linear ODE, where the dynamic variables (state) are the currents in the model's finite elements

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