Spectrum reference for RFP RWMs and MIMO controller synthesis

A control perspective on MHD modes in toroidal configurations

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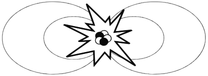

MHD Workshop, Columbia U., November 2007

Overview

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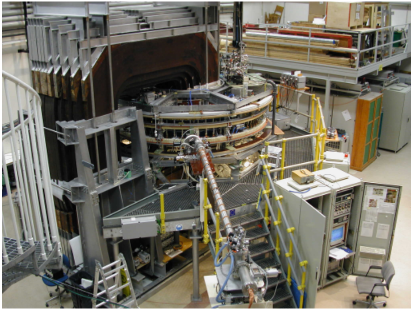
Successful experiments



- Multiple RWMs stabilized in EXTRAP-T2R
- Modeling of feedback: in qualitative agreement

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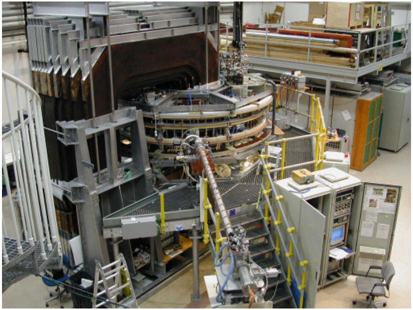

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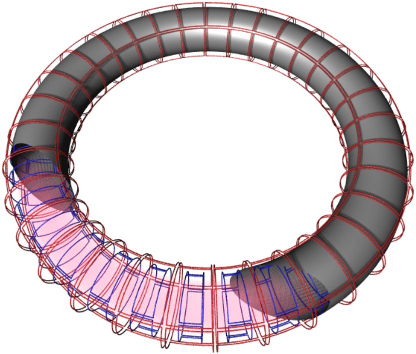
Typical methods



- Sensor-to-coil pairwise: local response
- Sensors-to-coils modewise: distributed response (FFT)

Enter a control perspective

- stabilization vs. control
- decentralized / centralized input/output pairing
- decoupled control (SVD methods)

Intelligent shell: decentralized stabilization
Mode control: decoupled stabilization
Both approaches in general suboptimal.

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More control lingo

- Robustness, *nominal* system
- 1-DOF/2-DOF regulator
- Cascade systems
- Sigma-plot $Y(s) = G(s)U(s)$:

$$\sigma_i(\jmath\omega) \equiv \sqrt{\lambda_i(G^*(\jmath\omega)G(\jmath\omega))}$$

$$\underline{\sigma}\{G(\jmath\omega)\} \leq \frac{|Y(\jmath\omega)|}{|U(\jmath\omega)|} \leq \overline{\sigma}\{G(\jmath\omega)\} \equiv |G(\jmath\omega)|$$

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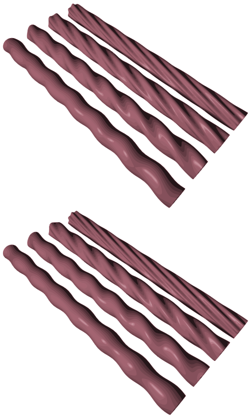
RWM perturbations: cylinder-model

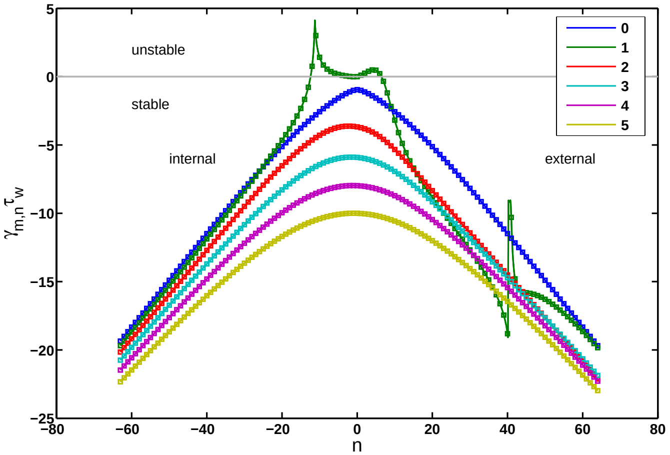


Spatially periodic perturbations of magnetic structure:

$$\tau_{m,n}\frac{\partial B_{m,n}}{\partial t} - \gamma_{m,n}\tau_{m,n}B_{m,n} = M_{m,n}I_{m,n}$$

where $B^{ext}_{m,n} = M_{m,n}I_{m,n}$.

Spectrum


unstable
stable
internal
external
0
1
2
3
4
5
$\gamma_{m,n}\tau_w$
n
5
0
−5
−10
−15
−20
−25
−80
−60
−40
−20
0
20
40
60
80

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   - H_∞-type loopshaping

State-space representation

Basic representation

$$\left\{\begin{array}{lcl} \dot{x} & = & Ax + Bu + Nv_1 \\ z & = & Mx \\ y & = & Cx + v_2 \end{array}\right. \qquad (1)$$

where

$$\begin{array}{lcl} A_{mn,m'n'} & \sim & \gamma_{mn}\delta_{mn,m'n'} \\ B_{mn,ij} & \sim & \tau_{mn}^{-1} \int_\Omega \left(\hat{\mathbf{r}}(\theta,\phi) \cdot \oint_{l_{ij}} \frac{\mathbf{dl}_{ij} \times (\mathbf{r}(\theta,\phi) - \mathbf{r}_{ij})}{|\mathbf{r}(\theta,\phi) - \mathbf{r}_{ij}|^3} \right) e^{-\iota(m\theta + n\phi)} d\theta d\phi \\ C_{pq,mn} & \sim & \int_\Omega f_{pq}(\theta,\phi) A_{pq}(\theta,\phi) e^{+\iota(m\theta + n\phi)} d\theta d\phi \end{array} \qquad (2)$$

for cylinder-model with perfectly symmetric shell conductivity.

Actuators and measurements

Note: (1)-(2) directly obtained from linear model with geometric consideration of sensors and active coils (actuators)

1. RWM dynamics: $\tau_{m,n}\dot{B}^{w}_{m,n} = \tau_{m,n}\gamma_{m,n}B^{w}_{m,n} + B^{ext}_{m,n}$
2. Actuator: $\mathbf{b}(\mathbf{r}) = \frac{\mu_0 n_c i_c}{4\pi}\oint_{l_c}\frac{\mathbf{dl}\times(\mathbf{r}-\mathbf{r}_c)}{|\mathbf{r}-\mathbf{r}_c|^3}$
3. Sensor: $u_s = -n_s\frac{\partial}{\partial t}\int_{S_s}\mathbf{b}\cdot\mathbf{dS}$

i.e laws of *Biot-Savart* and *Faraday*.

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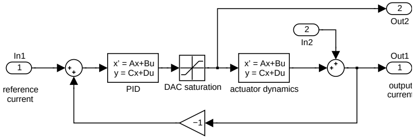
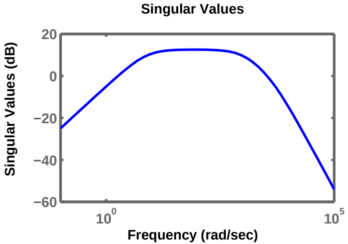
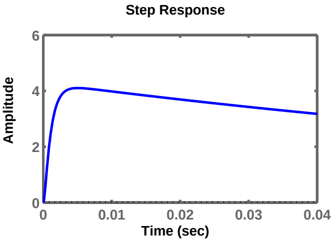
Peripheral dynamics

Dynamics of actuators (amplifier characteristics and coil L/R-times) *not* ignorable. A cascade-type PID-system employed.

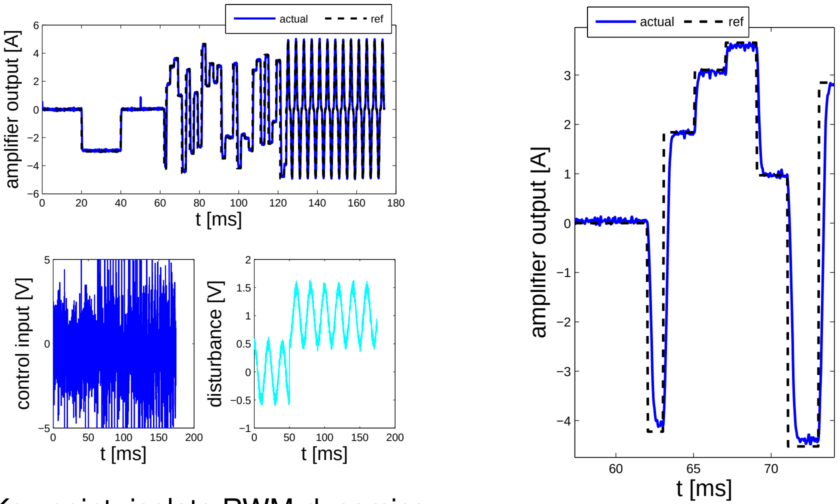


cascade current−control subsystem





Compensated SISO lumped amplifier & coil



Key-point: isolate RWM-dynamics.

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Control and observation *aliasing*

Rectangular schema of equal-size coils; typical complication of actuator and sensor: *aliasing*. Planar $M \times N$-DFT pair

$$\begin{aligned} F_{k,l} &= \frac{1}{\sqrt{MN}} \sum_{m,n} f_{m,n} e^{-2\pi i(mk/M+nl/N)} \\ f_{m,n} &= \frac{1}{\sqrt{MN}} \sum_{k,l} F_{k,l} e^{+2\pi i(mk/M+nl/N)} \end{aligned}$$

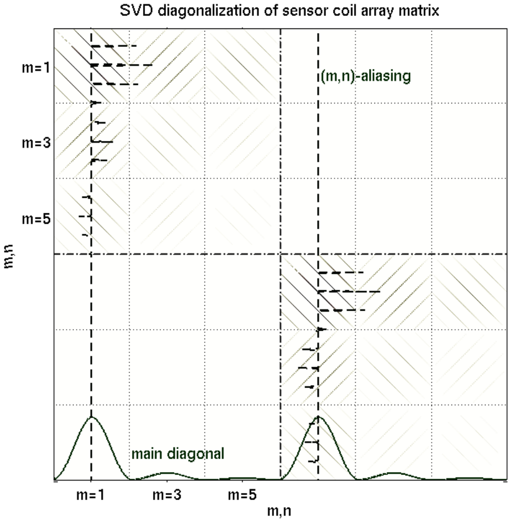
mapping $f \leftrightarrow F$. Periodicity[1]

$$F_{k+pM,l+qN} = F_{k,l} \text{ and } f_{m+pM,n+qN} = f_{m,n} \;\; \forall p, q \in \mathbb{Z}$$

is $M \times N$.

[1] also referred to as *sidebands*

Control and observation *aliasing*: SVD diagnose



SVD-demonstration of aliasing. Diagonalization-attempt (decoupling approach) BB^+.

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H_2 and H_∞

Typically

H_2: $||\mathbf{x}(t)||_{Q,2} \equiv \sqrt{\int_{-\infty}^{\infty} \mathbf{x}^T(\tau) Q \mathbf{x}(\tau) d\tau}$
Normally good for disturbance rejection requirements.

H_∞: $||\mathbf{x}(t)||_\infty \equiv \max_{i,\tau} |x_i(\tau)|$
Often used for enforcing robustness performance.

Performance channel: Denoted $\mathbf{z}$, z_j, a mathematically constructed output for design synthesis and comparison.

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Objective formulation

Use admissible inputs (active coil currents $\mathbf{u}(t)$) in the best way possible to keep a subset $\mathbf{z}(t)$ of MHD-mode trajectoria $\mathbf{x}(t)$ at a specified set-point (reference-spectrum vector $\mathbf{r}(t)$), by responding to plant output $\mathbf{y}(t)$ (sensor coil voltages).

Linear estimation and optimal filtering

Estimation: Given an interval of observations $\mathbf{y}(t)$, $t \in [t_A, t_B]$, form a clever guess of interesting quantity $\mathbf{z}(t)$.

Filtering: Do this in a real-time causal fashion.

Where a linear model is applicable: model-based filtering a la *Kalman* is standard procedure.

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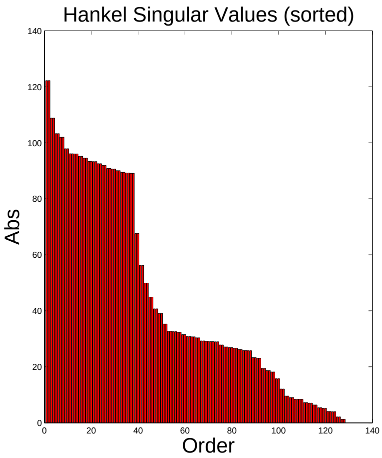
Employing model reduction

For rapid development (e.g. highly iterative controller synthesis), and real-time capabilities of synthesized controller-dynamics: reduction techniques. Definition of *Hankel* singular values

$$AP + PA^T + BB^T = 0$$

$$A^T Q + QA + C^T C = 0$$

$$\sigma_{Hankel,i} \equiv \sqrt{\lambda_i(PQ)}$$



Example: HSVs for a LQG controller

A word on Linear Matrix Inequalities

- Central concepts: Lyapunov stability, convex programming.
- Paradigm: multi-objective, selective channel convex optimization and conservatism.
- Objectives: H_2, H_∞, CL pole-region, etc.
- Unified formulation: LMI (Linear Matrix Inequality) constraints.
- Example (Lyapunov stability) $\dot{\mathbf{x}} = A\mathbf{x}$ stable iff

$$\exists \,\text{symmetric}\, P \text{ s.t. } P > 0,\; A^T P + PA < 0$$

meaning $M < 0 \Leftrightarrow \mathbf{q}^T M \mathbf{q} < 0 \;\forall \mathbf{q} \in \mathbb{R}^n \Leftrightarrow \lambda_{max}(M) < 0$, i.e. LMI feasibility problem.

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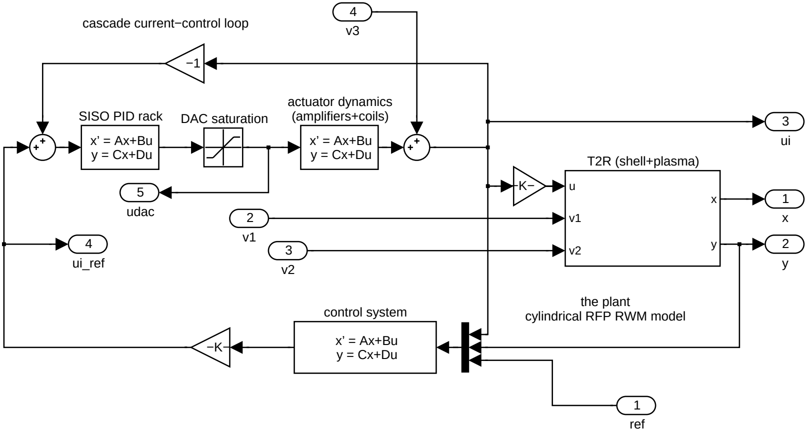
Test structure for EXTRAP-T2R spectrum control



Overview

Theory

Reconstructed-state feedback. Solves a quadratic cost functional minimization:
$J_{Q_1 Q_2} = \mathrm{E}\left\{\int \left(z^T Q_1 z + u^T Q_2 u\right) dt\right\}$. Design involves tuning of both KF and LQ. Controller:

$$\left\{\begin{array}{lcl} u & = & -L\hat{x} \\ \dot{\hat{x}} & = & A\hat{x} + Bu + K(y - C\hat{x}) \end{array}\right.$$

where
$$AP + PA^T + NR_1 N^T - (PC^T + NR_{12})R_2^{-1}(PC^T + NR_{12})^T = 0$$
$$K = (PC^T + NR_{12})R_2^{-1}$$
and
$$A^T S + SA + M^T Q_1 M - SBQ_2^{-1} B^T S = 0$$
$$L = Q_2^{-1} B^T S$$

Modified plant for field-error compensation:

$$\frac{d}{dt}\begin{pmatrix} x \\ z_s \end{pmatrix} = \begin{pmatrix} A & NM^T \\ 0 & -\delta I \end{pmatrix}\begin{pmatrix} x \\ z_s \end{pmatrix} + \begin{pmatrix} B \\ 0 \end{pmatrix} u + \begin{pmatrix} N \\ I \end{pmatrix} v_1$$
$$z = \begin{pmatrix} M & 0 \end{pmatrix}\begin{pmatrix} x \\ z_s \end{pmatrix}$$
$$y = \begin{pmatrix} C & 0 \end{pmatrix}\begin{pmatrix} x \\ z_s \end{pmatrix} + v_2$$

Theory: keeping it compact

1. Starting from nominal plant (1), formally augment output:

$$\dot{x} = Ax + Bu + Nv_1\,, \quad \begin{pmatrix} z \\ y \end{pmatrix} = \begin{pmatrix} M \\ C \end{pmatrix} x + \begin{pmatrix} 0 \\ I \end{pmatrix} v_2 \tag{3}$$

2. Apply aggressive model-reduction to (3) yielding

$$\dot{x} = \bar{A}x + \bar{B}u, \quad \begin{pmatrix} z \\ y \end{pmatrix} = \begin{pmatrix} C_1 \\ C_2 \end{pmatrix} x + \begin{pmatrix} D_1 \\ D_2 \end{pmatrix} u \tag{4}$$

   emerged: direct-terms C_i, D_i.

3. Augment (4): static field x_s, $\dot{x}_s = 0$ thus

$$\frac{d}{dt}\begin{pmatrix} x \\ x_s \end{pmatrix} = \begin{pmatrix} \bar{A} & \bar{N} \\ 0 & 0 \end{pmatrix} \begin{pmatrix} x \\ x_s \end{pmatrix} + \begin{pmatrix} \bar{B} \\ 0 \end{pmatrix} u, \quad \begin{pmatrix} z \\ y \end{pmatrix} = \begin{pmatrix} C_1 & 0 \\ C_2 & 0 \end{pmatrix} \begin{pmatrix} x \\ x_s \end{pmatrix} + \begin{pmatrix} D_1 \\ D_2 \end{pmatrix} u \tag{5}$$

Theory: keeping it compact, contd.

4. Compute KF for (5) hence form observer

$$\frac{d}{dt}\begin{pmatrix}\hat{x}\\ \hat{x}_s\end{pmatrix} = \begin{pmatrix}\bar{A} & \bar{N}\\ 0 & 0\end{pmatrix}\begin{pmatrix}\hat{x}\\ \hat{x}_s\end{pmatrix} + \begin{pmatrix}\bar{B}\\ 0\end{pmatrix} u + K(y - C_2\hat{x} - D_2 u) \tag{6}$$

   This step ignores (C_1, D_1).

5. Compute LQ state-feedback gain L for (4) involving $||\cdot||_2$-cross-terms

$$J_{Q_1,Q_2} = \mathrm{E}\int \begin{pmatrix}x\\ u\end{pmatrix}^T \begin{pmatrix}C_1^T Q_1 C_1 & C_1^T Q_1 D_1\\ \star & D_1^T Q_1 D_1 + Q_2\end{pmatrix}\begin{pmatrix}x\\ u\end{pmatrix} dt \tag{7}$$

   This step ignores (C_2, D_2).

6. Finding static-gains and sum up control u:

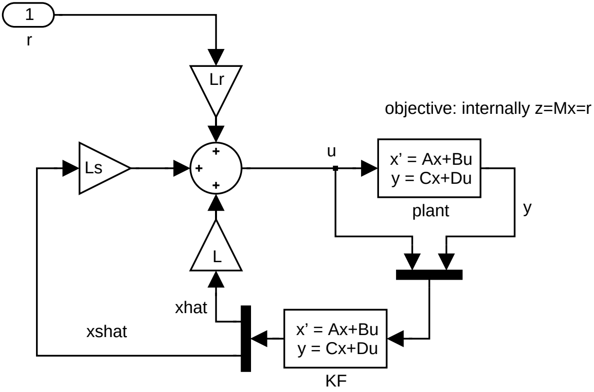
$$L_r = (-\bar{B}^{-1}\bar{A} - L)(C_1 - D_1\bar{B}^{-1}\bar{A})^{-1} \tag{8a}$$

$$L_s = -\bar{B}^{-1} \tag{8b}$$

$$u = L\hat{x} + L_s\hat{x}_s + L_r r \tag{8c}$$

done. Control system (6) with (8c), inputs: (u, y, r), output u_{set}.

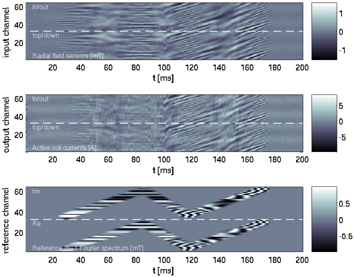
Structure

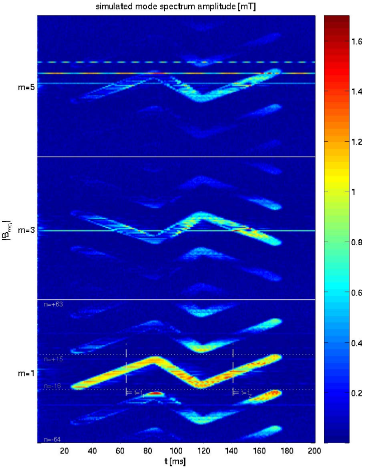


Signal routing for LQG test.

Result

- 128-state control-system (192 inputs, 64 outputs)
- spectrum sweep-type reference
- model-mismatch, eigenvalue perturbations
- static-field errors, noise everywhere
- fictitious shot: 200ms





Overview

loopsyn theory

Method: observer + normalized coprime factorization synthesis; MATLAB: Robust Control Toolbox; doc loopsyn.

$$\gamma\underline{\sigma}\left\{G_z(\jmath\omega)F(\jmath\omega)\right\} \geq \overline{\sigma}\left\{G_d(\jmath\omega)\right\} \qquad \omega < \omega_0$$
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where γ is the minimized H_∞-performance measure.

Strategy:

1. Form plant $G_z : u \longrightarrow z$ from nominal modeling
2. Design parameter: desired loop-shape G_d Typically $G_d(s) \sim \frac{\omega_{c,des}}{s}$
3. Apply loopsyn to G_z, yield control-law K with H_∞-performance γ
4. Connect K to an observer (here KF) of z: $\hat{z}$

- Technique similar to hinfsyn & h2syn
- NB: KF important by itself (overlooked/blackboxed by direct output-feedback synthesis)

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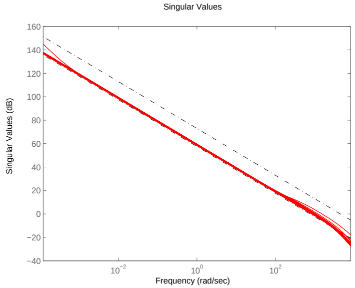
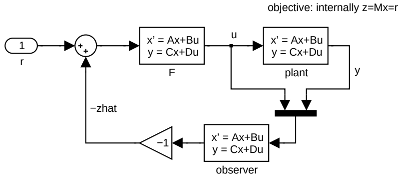
`loopsyn` applied





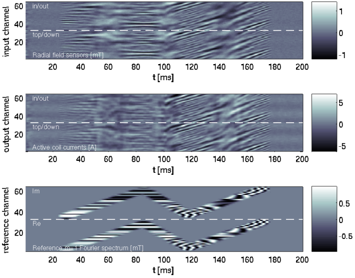
Sigma-plot: $\sigma\left\{G_z(\jmath\omega)F(\jmath\omega)\right\}$ with H_∞-bound, in decibels as a function of angular frequency ω.

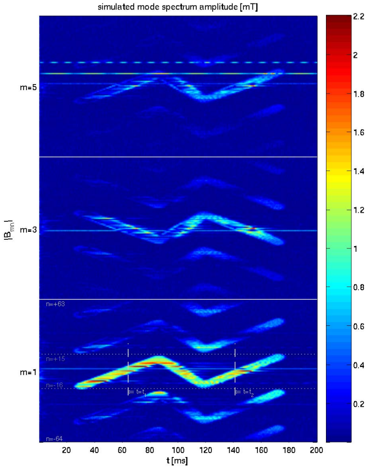
Control structure: observer + loopshaping F.

H_∞-type loopshaping

Result

- same scenario as for LQG-test
- more complex controller; but reducible





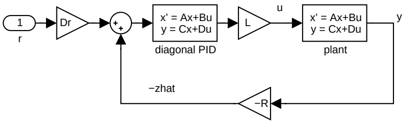
Comparison

Why complicate?

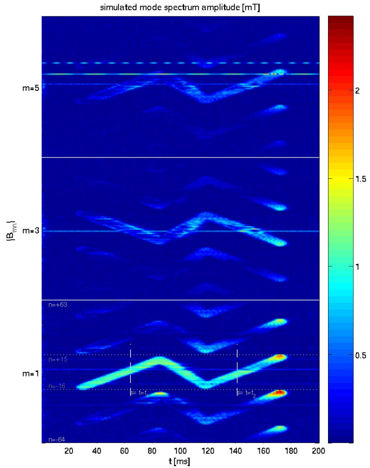
SVD-decoupled PID-control:

$$\mathbf{u}(t)_{set} = B^+ M^T F_{PID}(s)(D_r \mathbf{r}(t) - \eta M C^+ \mathbf{y}(t)) \quad (9)$$
$$F_{PID}(s), \ \text{diagonal} \quad (10)$$
$$D_r, \ \text{diagonal: s.t. } G_c(s) \sim I \text{ for } \omega \sim 0 \quad (11)$$

Structure:



Static state estimation.



Comparison

A last example:

Precision:	Specifically transient precision significantly improved.
Generality:	More involved geometries. Heavily constrained actuator coverage. Optimal use of available sensors.
Mode-coupling:	Multi-m eigenfunctions, dispersive field diffusion: static estimator insufficient.
Physics:	Experiments need precision. Studies in plasma dynamics.

Yes, complicate.

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H_∞-type loopshaping

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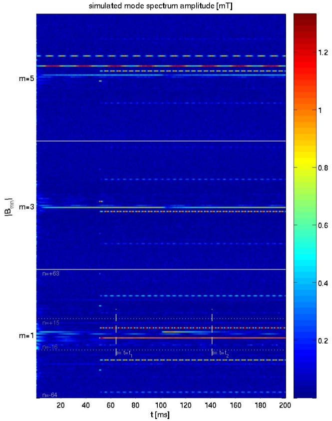
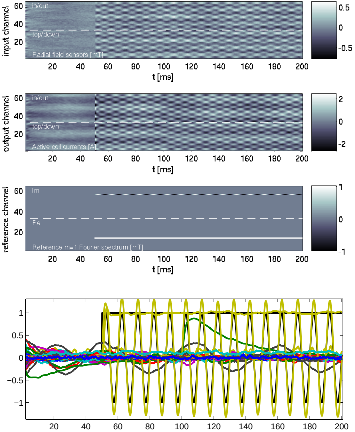
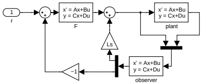
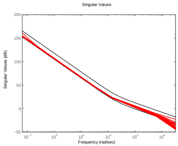


Last points





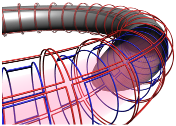


$$G_d(s) = \frac{\omega_C}{s}\frac{\omega_I + s}{s}, \quad \omega_I < \omega_C$$

Feedforward: Reproducible error-fields. Isolate RWM-control problem.

Quick-solution: Pre-set observer initial state. Trigger.

Summary



- Using recent methods for control design
- Model-based; validate and harness
- Extend experimental possibilities
- Some things todo:
  - Implement and experiment
  - Improve modeling
  - Apply to specific tokamak geometries
  - MHD signal processing

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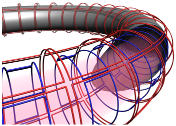

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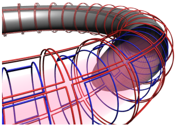

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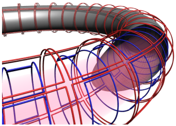

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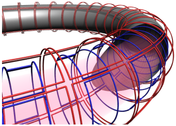

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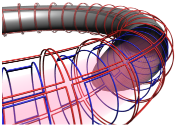

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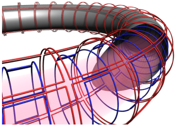

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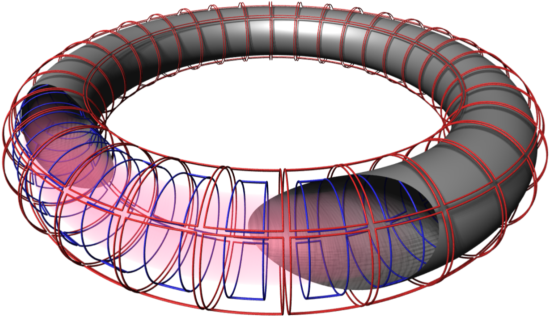

Soon: a firm grip on magnetic structure?