Ideal Orbit Feedback for Ultra-low Emittance Rings

Guenther Rehm

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Outline

- The Motivation of Orbit Feedback
- Bandwidth and Latency
- Simple Feedback and Internal Model Control
- Whole Orbit Control
- Orbit Response Matrix Inversion
- Summary

References and further reading

Overviews:

[1] J. Bechhoefer, “Feedback for physicists: A tutorial essay on control,” *Rev. Mod. Phys.*, vol. 77, no. 3, pp. 783–836, Aug. 2005.

[2] A. Chao et.al., “Handbook of Accelerator Physics and Engineering”, pp. 624-628, World Scientific, 2013, 2nd Ed.

[3] D. Bulfone, “Overview of Fast Beam Position Feedback Systems,” in *Proc. of EPAC*, 2008, pp. 1021–1025.

Details:

[4] P. Kallakuri et.al., “Modelling the Fast Orbit Feedback Control System for APS Upgrade,” in *Proc. of IBIC2017*, 2017.

[5] S. Gayadeen, et. al. , “A Unified Approach to the Design of Orbit Feedback with Fast and Slow Correctors,” in *Proc. of ICALEPCS*, 2015, pp. 494–497.

[6] N. Hubert, et al. "Global orbit feedback systems down to DC using fast and slow correctors," in *Proc. of DIPAC,* 2009.

[7] A. Terebilo, et.al. "Fast global orbit feedback system in SPEAR3." *Proc. of EPAC*, 2006.

[8] S. Duncan, “The Design of a Fast Orbit Beam Stabilisation System for the Diamond Synchrotron”, report 2296/07, Oxford University

PhD Thesis

[8] R. Steinhagen, “LHC Beam Stability and Feedback Control,” RWTH Aachen, 2007.

[9] S. Gayadeen, “Synchrotron Electron Beam Control,” University of Oxford, 2014.

A bit of Feedback Language

- **Monitor**: Beam Position Monitor, Orbit
- **Actuator**: Corrector Magnets including their power supplies
- **Plant, Process**: The controlled equipment, for us the stored beam orbit
- **Controller**: The control algorithm and its implementation
- **Latency**: Various delays like transport delays, calculation delays
- **Transfer function**: complex model of Out/In, a function of $s = i\omega$
- **SISO**: Single Input Single Output
- **MIMO**: Multi Input Multi Output
- **Mode**: a spatial orbit pattern
- **dB**: a unit of log power ratio defined $10 * \log_{10} \frac{P_1}{P_2} = 20 * \log_{10} \frac{A_1}{A_2}$

The Source of Orbit Deviations

- Small scale dipole deviation will create an orbit deviation of the shape:

$$\Delta x(s) = \Delta x'(s_0)\sqrt{\beta_x(s_0)\beta_x(s)} \times \frac{\cos(|\psi_x(s) - \psi_x(s_0)| - \pi\nu_x)}{2\sin\pi\nu_x},$$

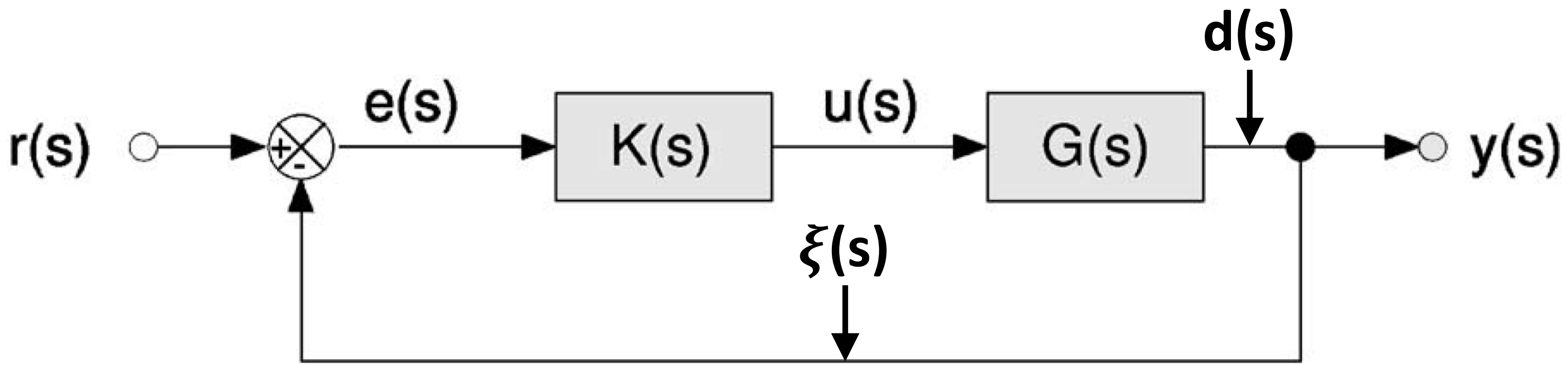
From [2]

- The $\sin \pi\nu_{x/y}$ term in the denominator acts as a scaler to ALL orbit deviations

The Goal of Orbit Feedback

- To keep the orbit of the stored beam in a storage ring within:
  - **specified deviations**
    - Typically 10% of RMS beam size is allowed as RMS motion
    - Only useful if integrated over by the experiment (talk to users), otherwise aim at 2-3%
    - Must be accompanied by range, order of 1mHz – 1000Hz
  - from **desired positions**
    - First aim is beam based alignment centre of nearby quadrupole
    - Needs to be reliable thereafter, minimise electrical and mechanical drifts (cables, electronics, temperature, foundations etc.)
    - In light sources, photon beam position monitors might turn out to be more relevant longer term
  - at all **observed locations**
    - Betatron waves in both planes sufficiently spatially sampled (aim at 4 BPMs per period)
    - Typically 100s of Beam Position Monitor (BPM) locations around the ring

A simple feedback loop

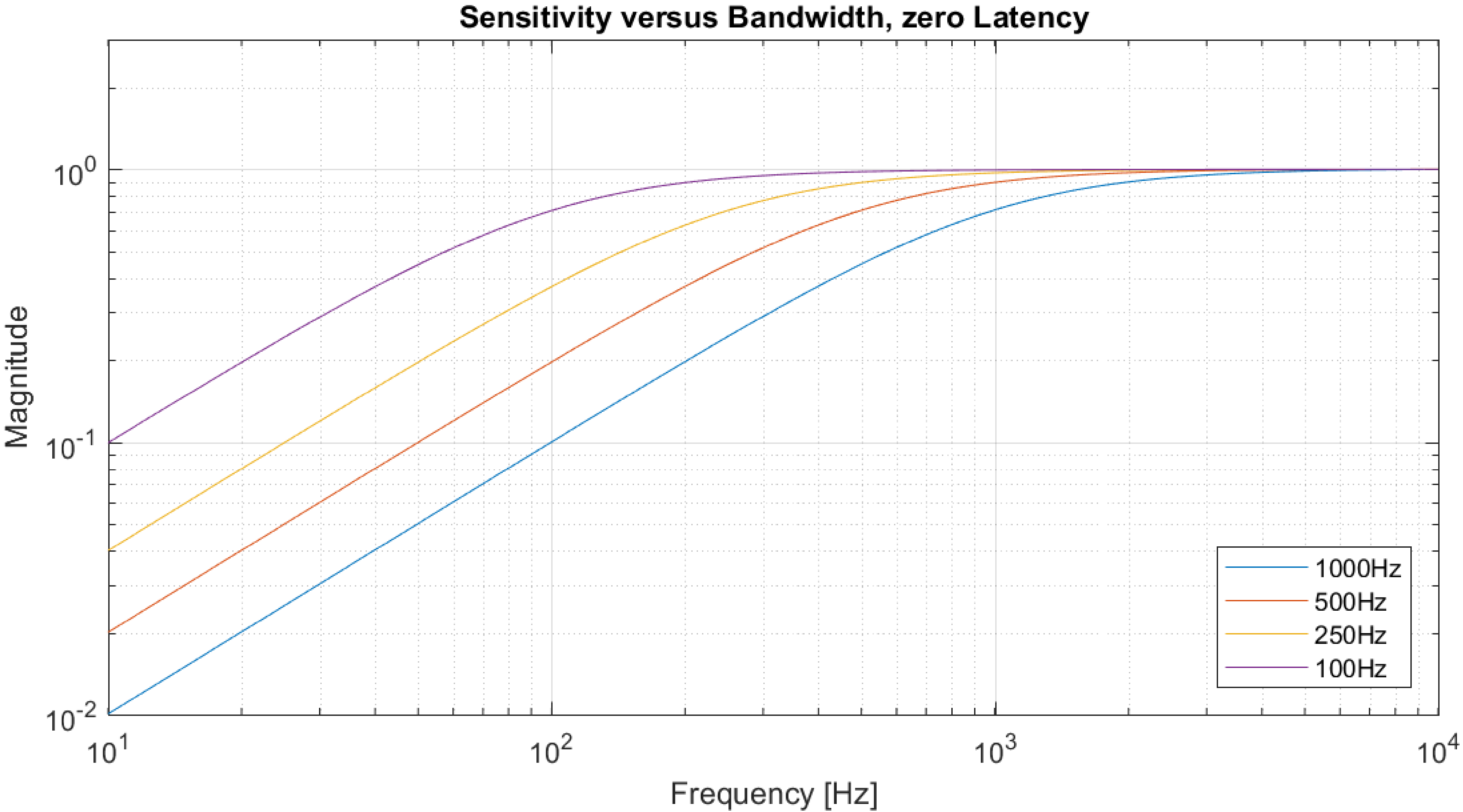


$$y(s) = \frac{K(s)G(s)}{1 + K(s)G(s)} r(s) \qquad y(s) = \frac{KG}{1 + KG}[r(s) - \xi(s)] + \frac{1}{1 + KG} d(s)$$

From [1]

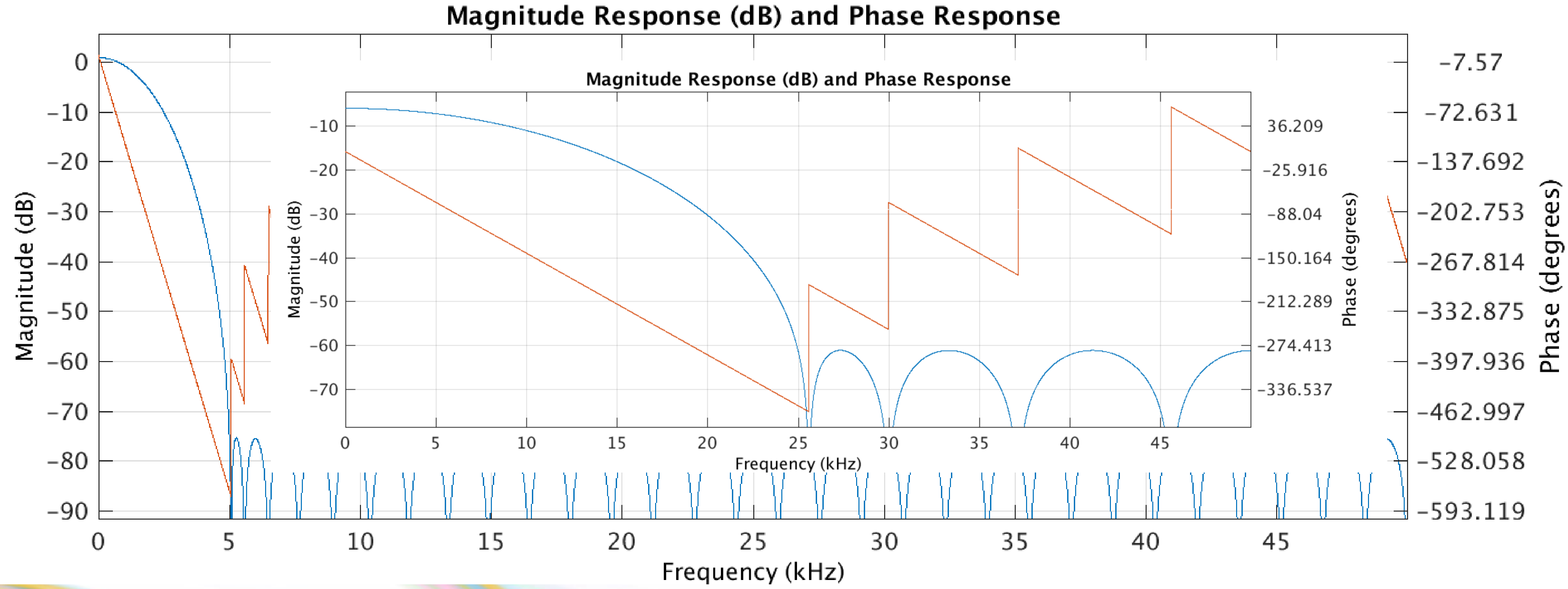
- G(s): Transfer function of the plant, including actuator and monitor dynamics (beam orbit including corrector and BPM dynamics)
- K(s): Transfer function of the controller
- e(s): feedback error
- r(s): set point
- u(s): actuator values (corrector magnet values)
- y(s): monitor values (BPM values)
- d(s): disturbance (here shown on the orbit, could equally be shown adding to u(s)
- ξ(s): BPM uncertainties/noise

If only the world was so simple…



BPM frequency response

- Almost all modern BPMs use finite impulse response (FIR) low pass filters
- This will cause systematic latency of generally half their length
- **Sharper** drops will cause **longer** latency, slower require higher output sample frequency
- Latency is visible as linear phase slope as delay causes $e^{-s\Delta T}$

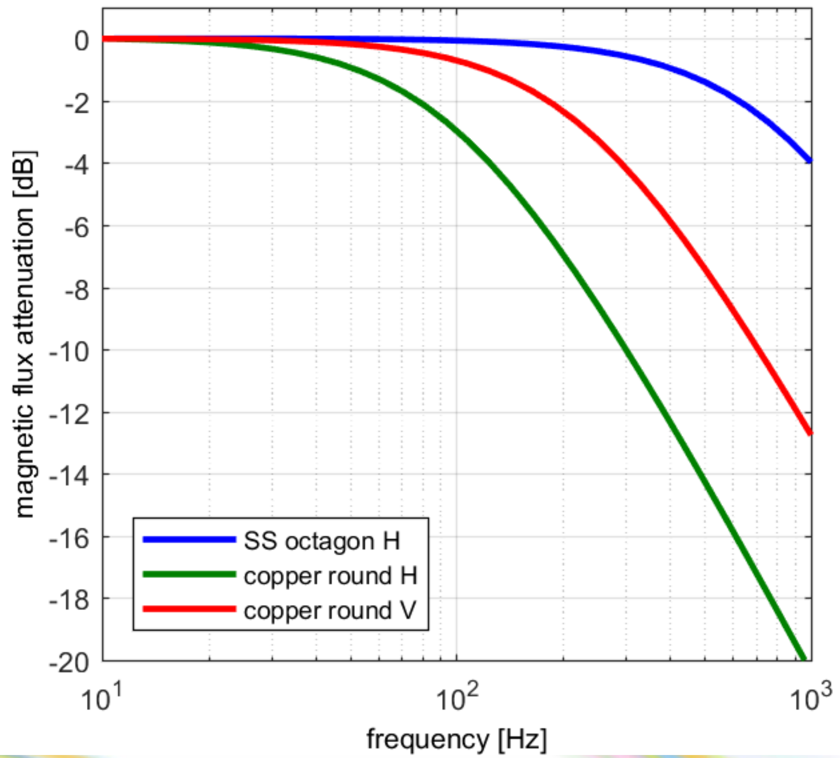


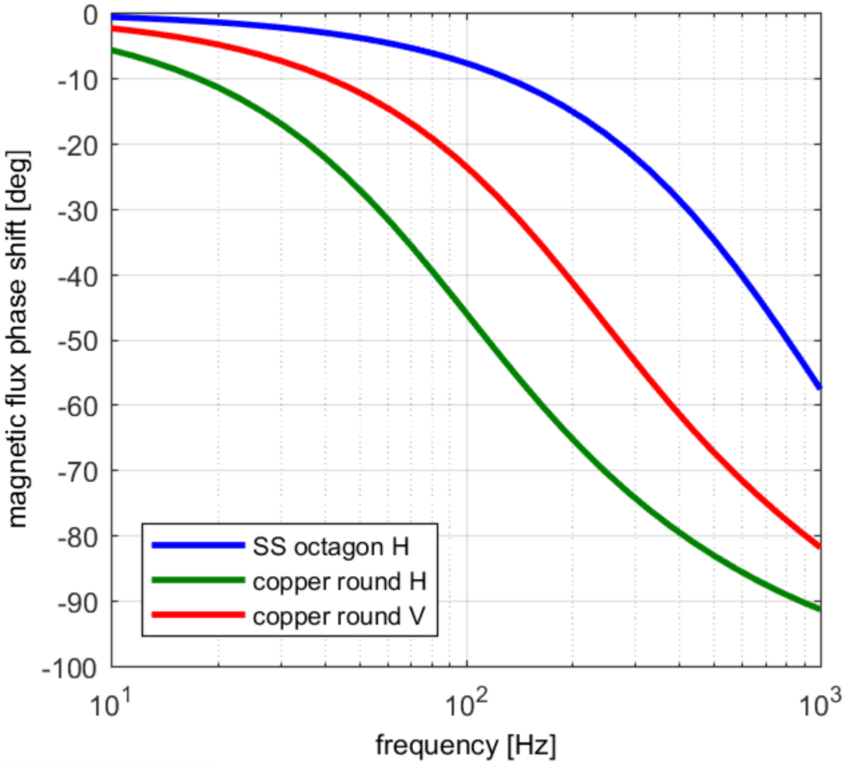
BPM technology evolution

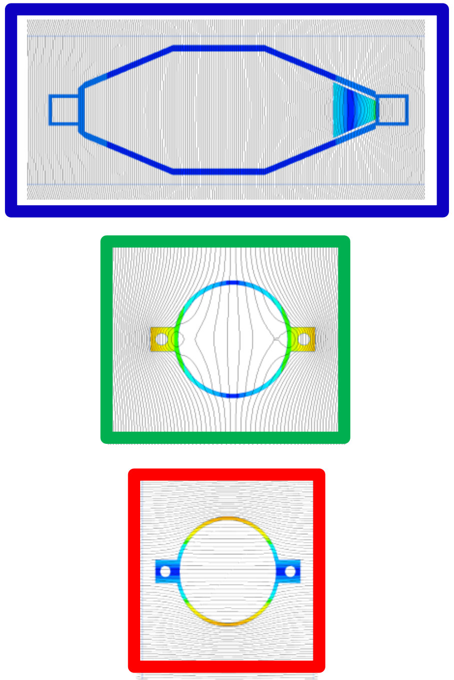
- BPMs today are integrated with digitisation, often at high speed (>100MS/s), and subsequent averaging/filtering to lower speeds for orbit transfer.
- Choice of speed for orbit transfer depends on network technology, 2Gb/s is the past, 6.5Gb/s on current commercial equipment, 10+Gb/s are available without big complication.
- It is this speed and the update rate of orbit reading which will ultimately cause latency, thus aim as high as you can.

Magnet and Vessel Transfer Functions

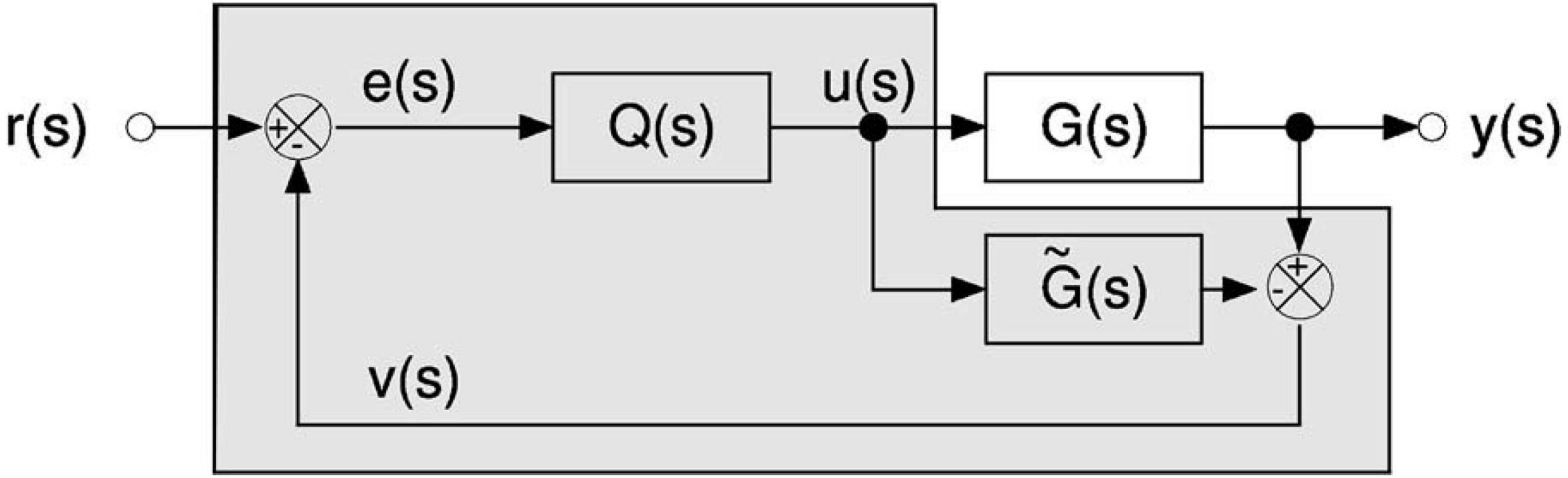
- Magnets slow down due to eddy currents in the joke, choose laminated, ferrite or air core for correctors.
- Vessels can show significant eddy currents effects for high conductivity material (Cu, Al).
- Simulations are required to estimate effects on geometries with cooling channels or other features attached







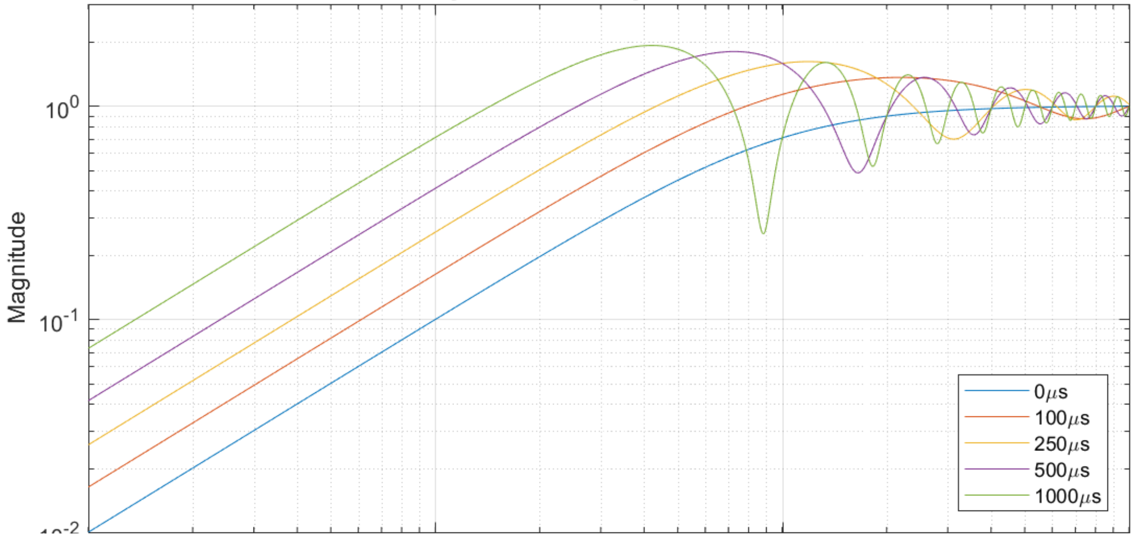
Internal Model Control



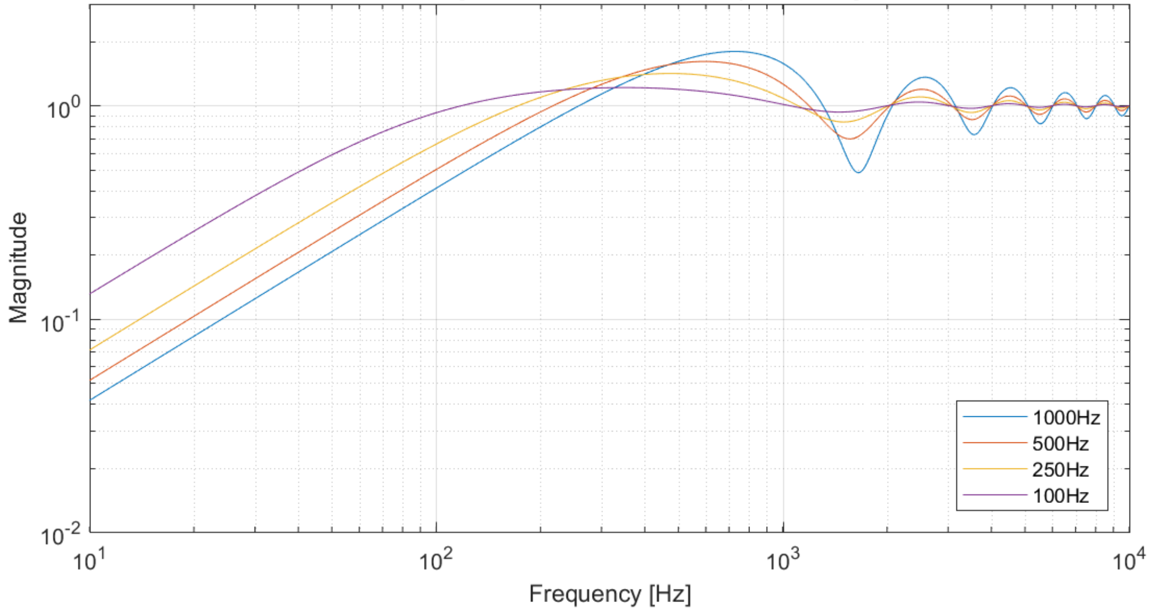
From [1]

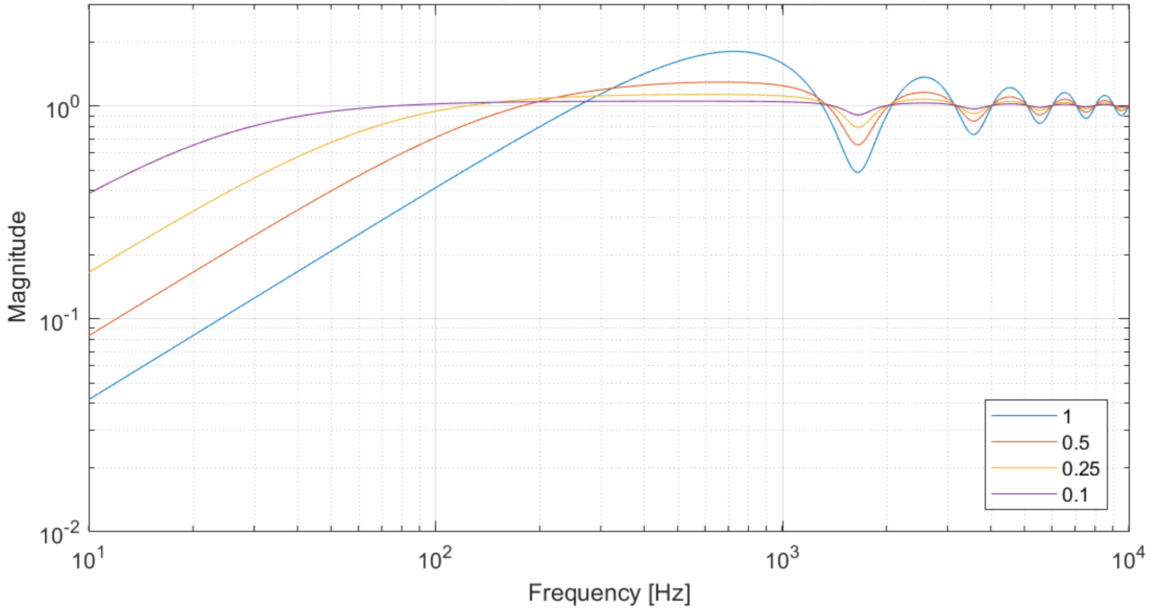
- $\tilde{G}(s)$: Transfer function of the model, monitor and actuator dynamics and latency, provides predictions of plant behaviour
- Q(s): IMC controller
- This system is one way to explicitly address the significant latency as found in digital systems
- Solution for a simple 1-pole low pass model is straight forward and feature three parameters: **latency, bandwidth and gain**

Latency, Bandwidth, Gain


Sensitivity versus Latency, 1000 Hz bandwidth

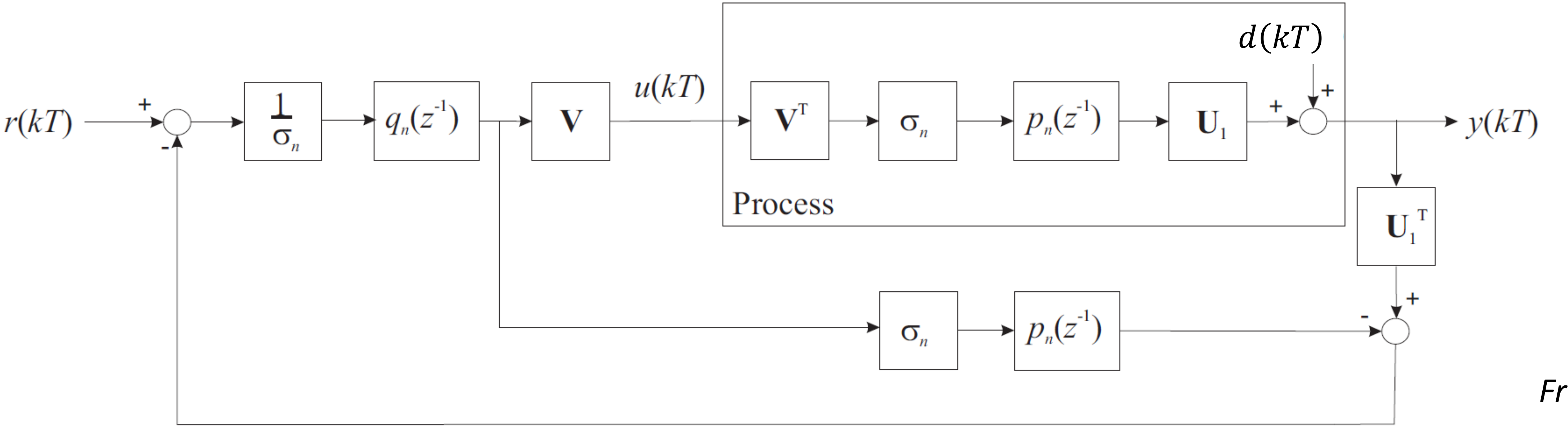
- Increasing latency or decreasing bandwidth both limit performance (lower crossover of gain 1)
- Reducing gain also reduces performance, but differently
- Most importantly, this is the only parameter that remains to chose later


Sensitivity versus Bandwidth, 500µs Latency


Sensitivity versus gain, 1000 Hz bandwith, 500µs latency

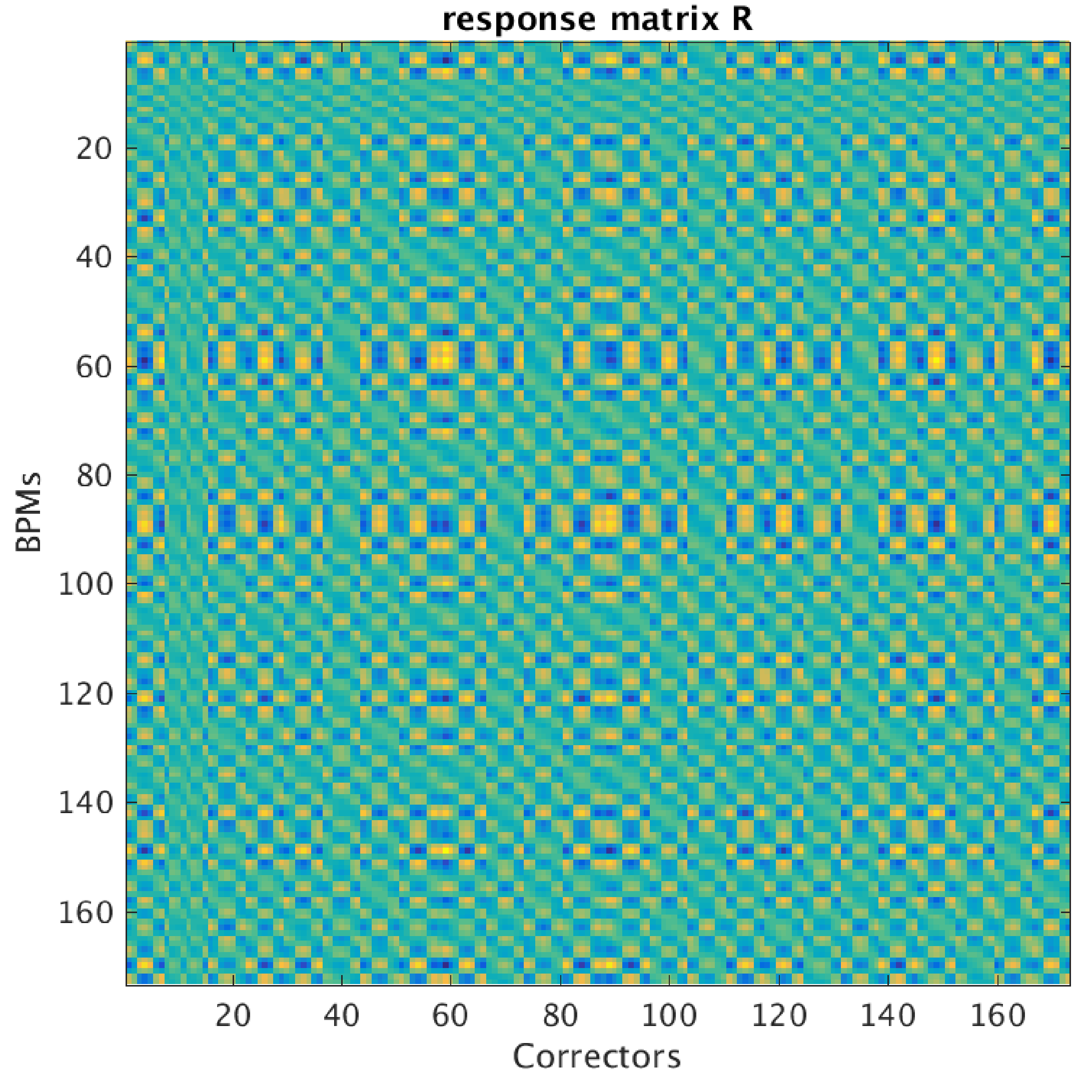
SISO to MIMO, continuous to sampled

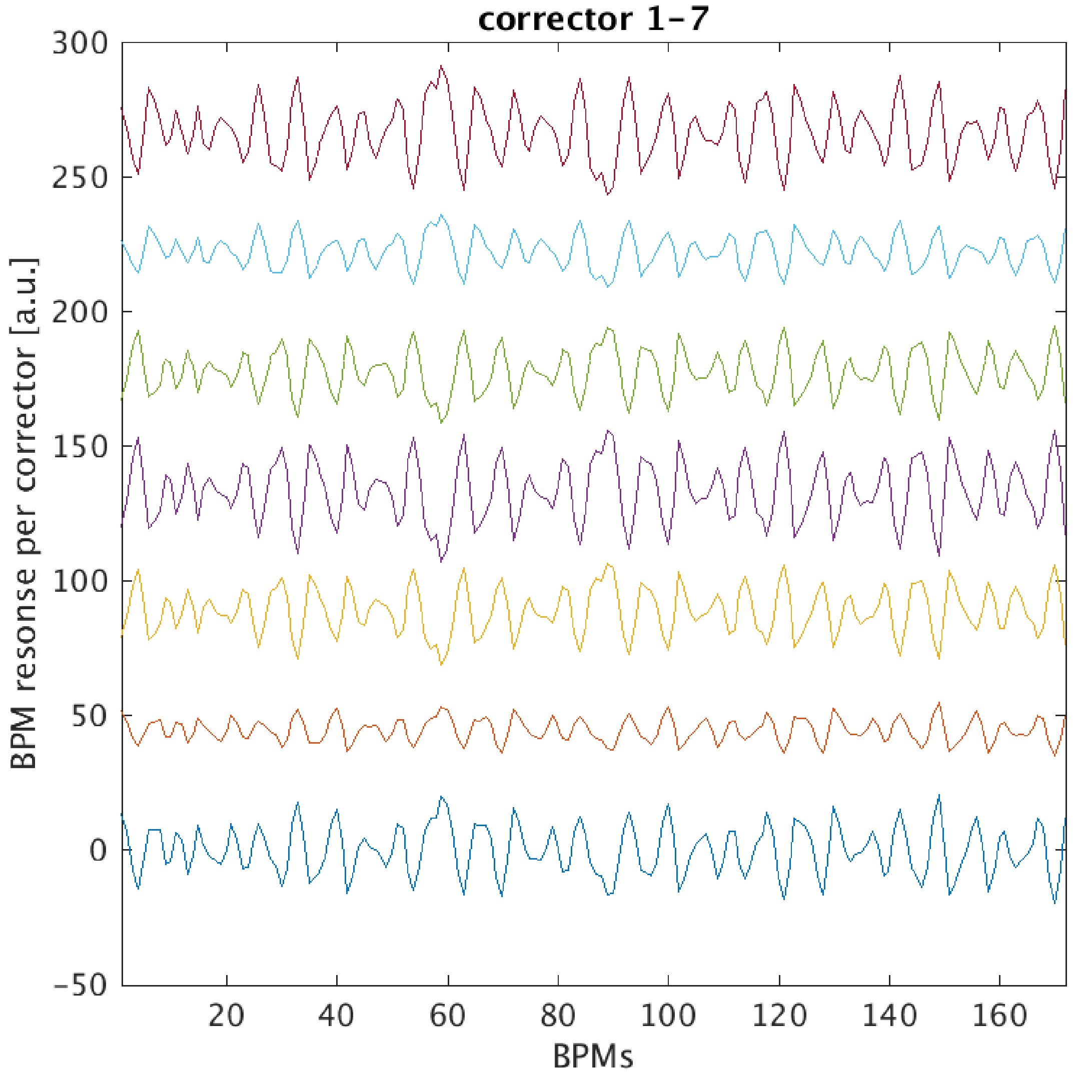
- In orbit feedback, we have multiple BPMs and multiple correctors.
- Controller needs to be a MIMO controller.
- But we get away with separation the static ORM and separate (initially identical dynamics) of all the modes.
- Also for digital controller design, we need to consider a sampled system.
- Matrix inversion of the ORM is required in the controller and done using SVD: $\boldsymbol{R} = \boldsymbol{U\Sigma V}^T$ $\quad \boldsymbol{R}^+ = \boldsymbol{V\Sigma}^{-1}\boldsymbol{U}^T$ Works for non-square ORM just as well.



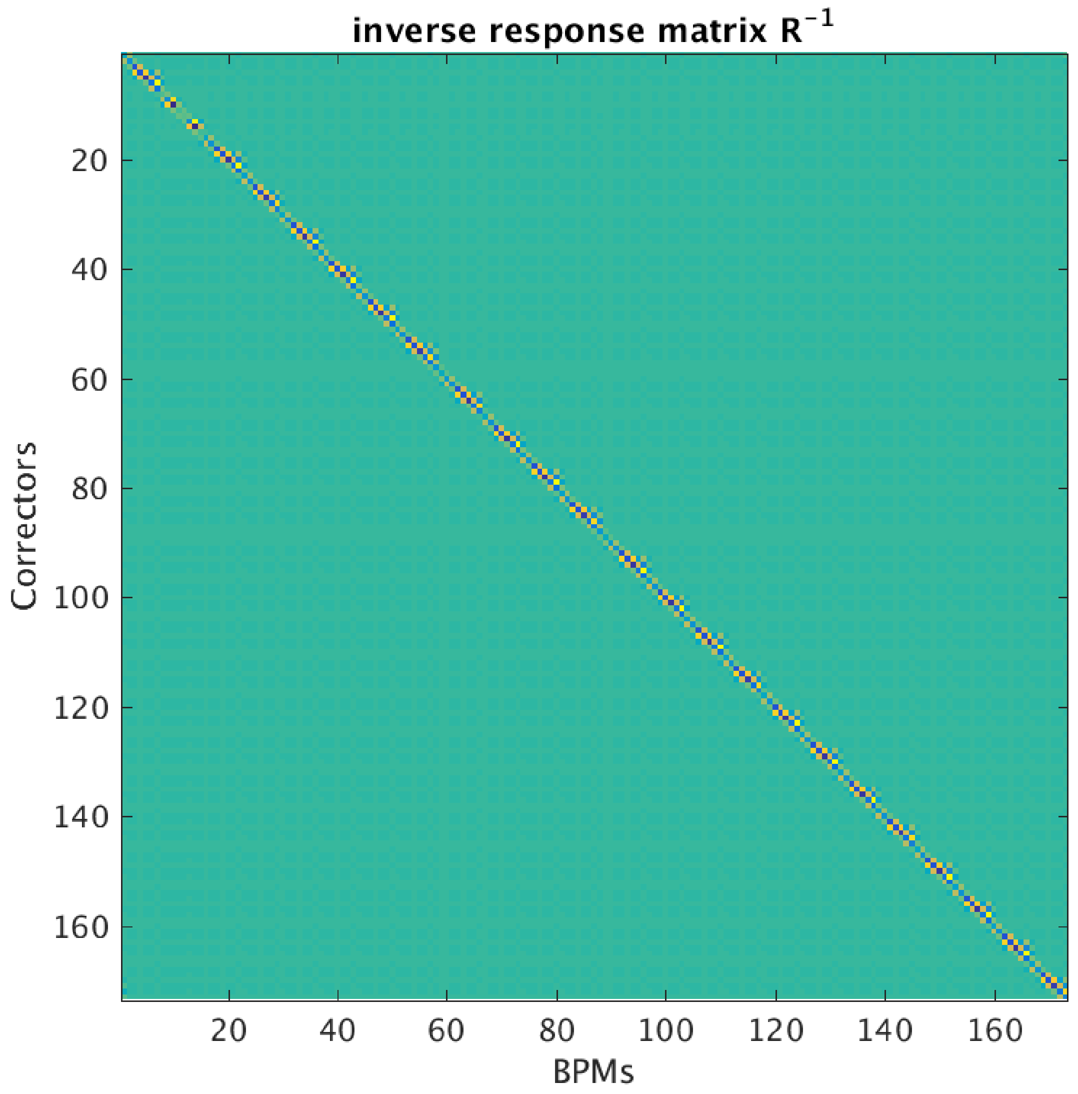
From [8]

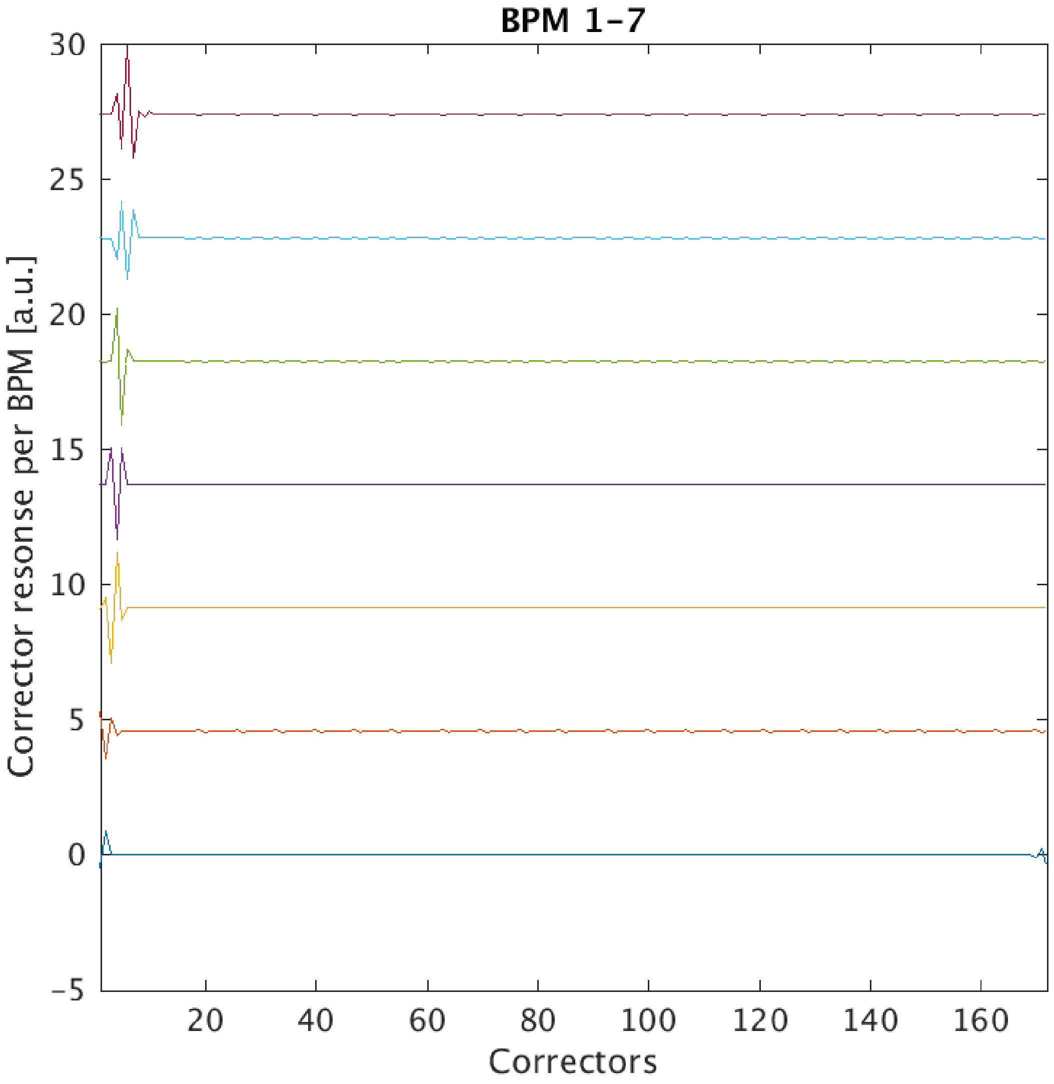
Orbit Response Matrix



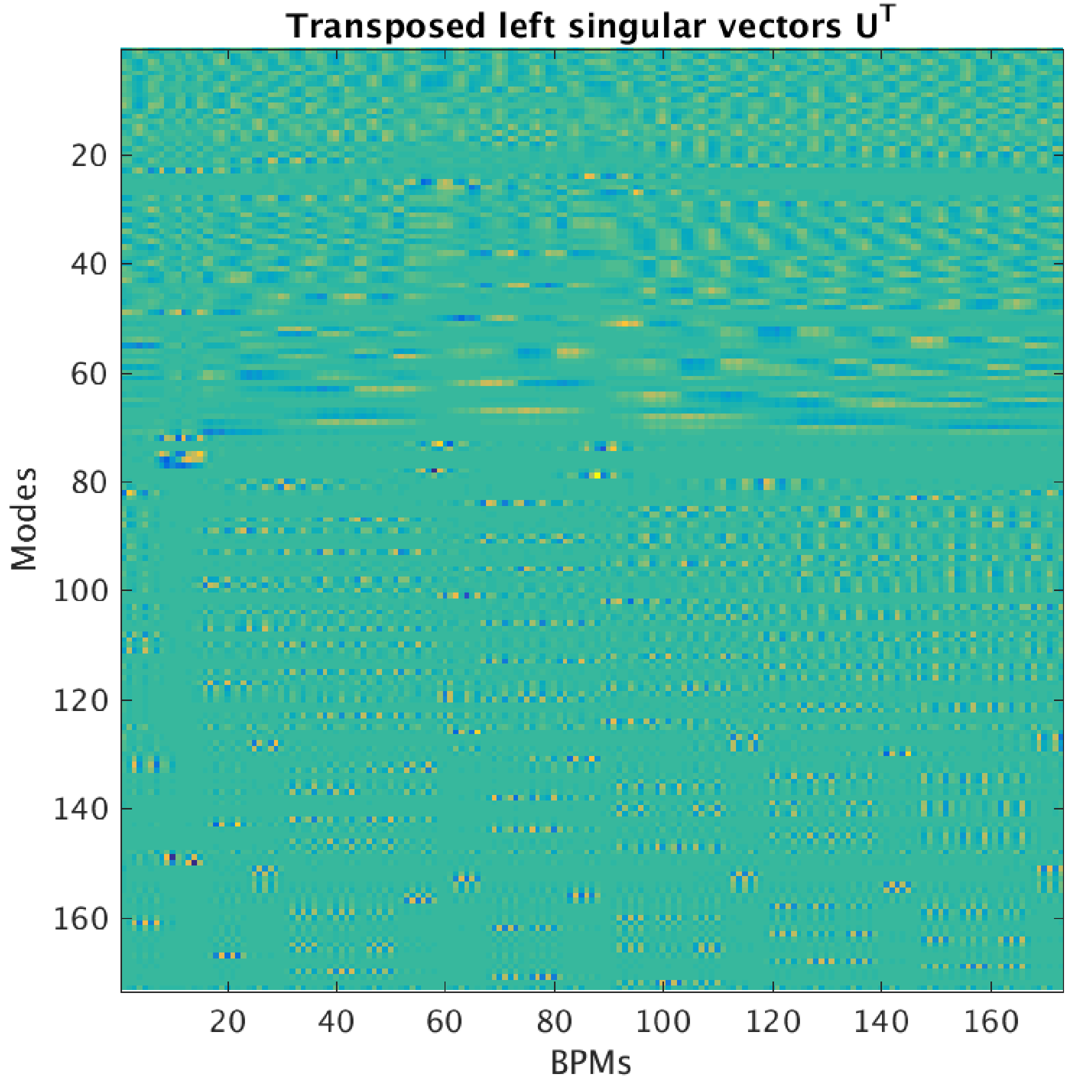


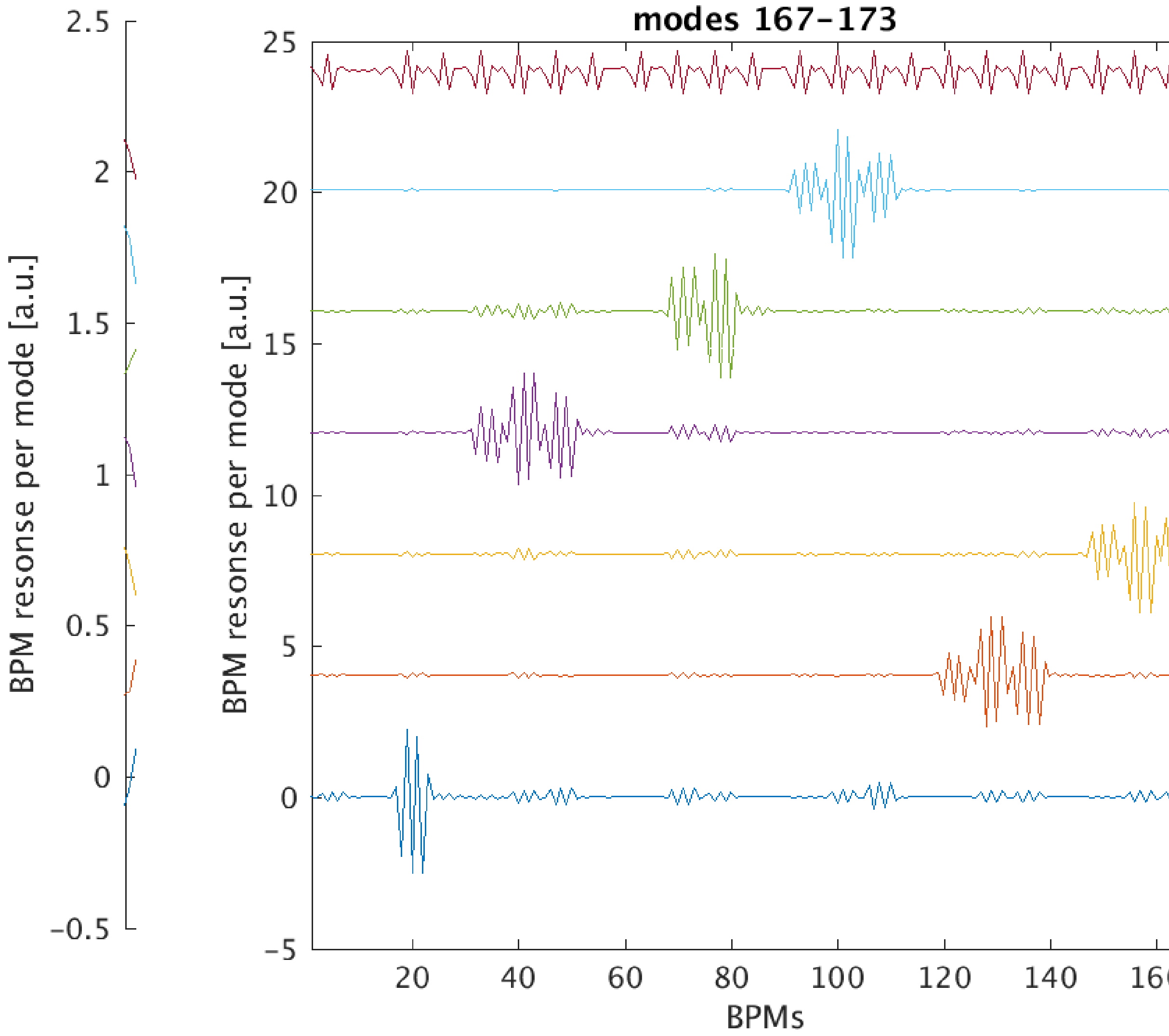
Inverse Orbit Response Matrix



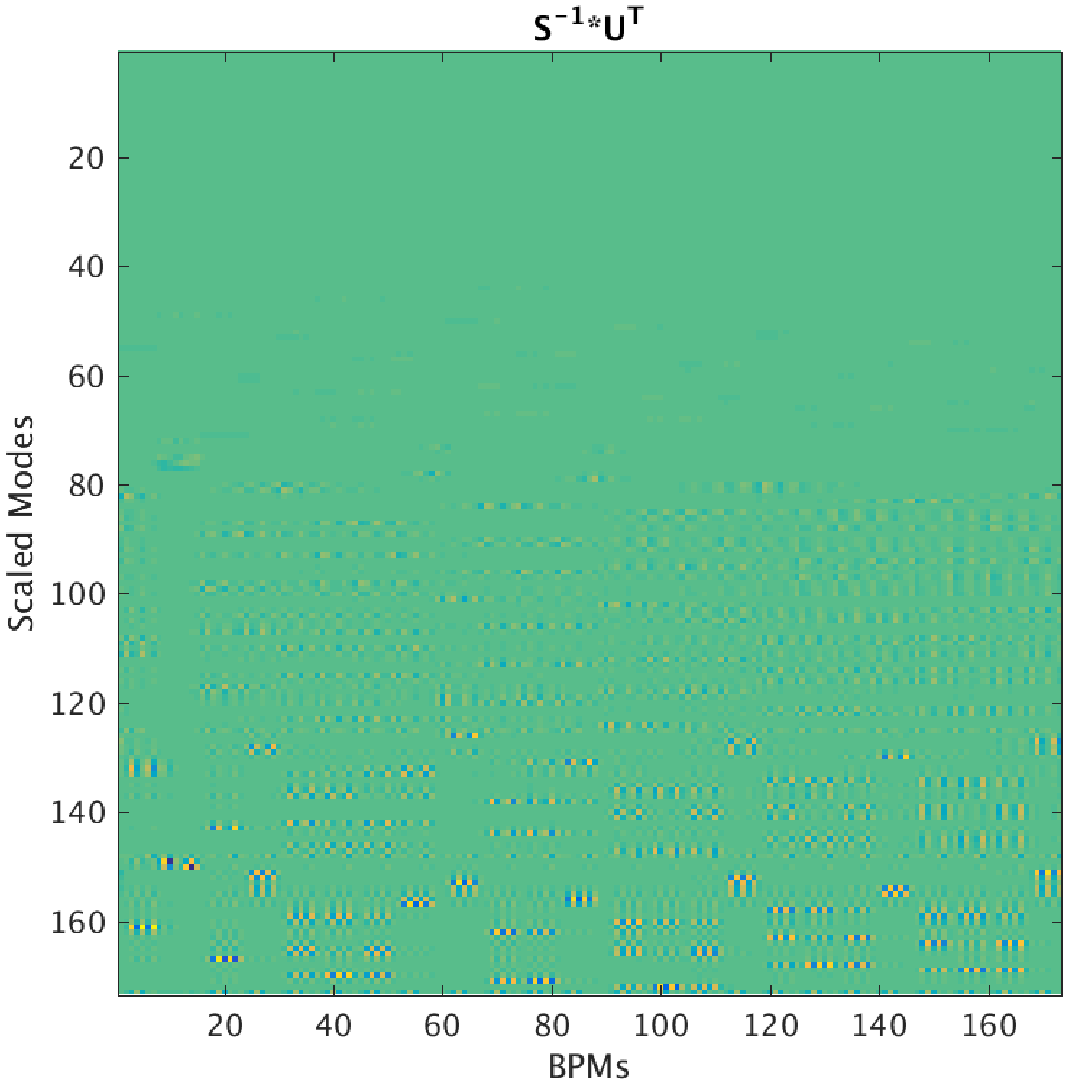


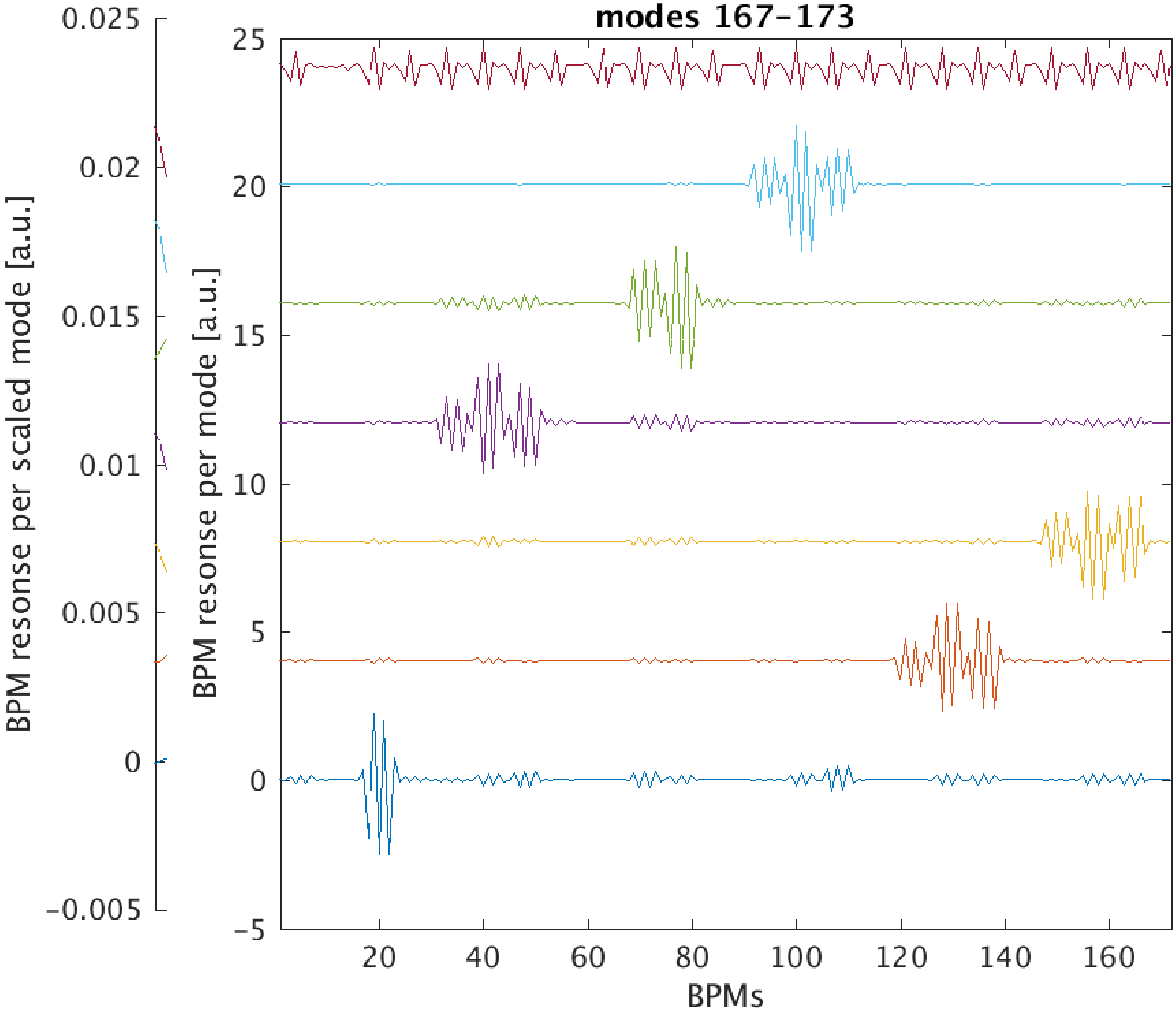
Under the Hood of SVD 1





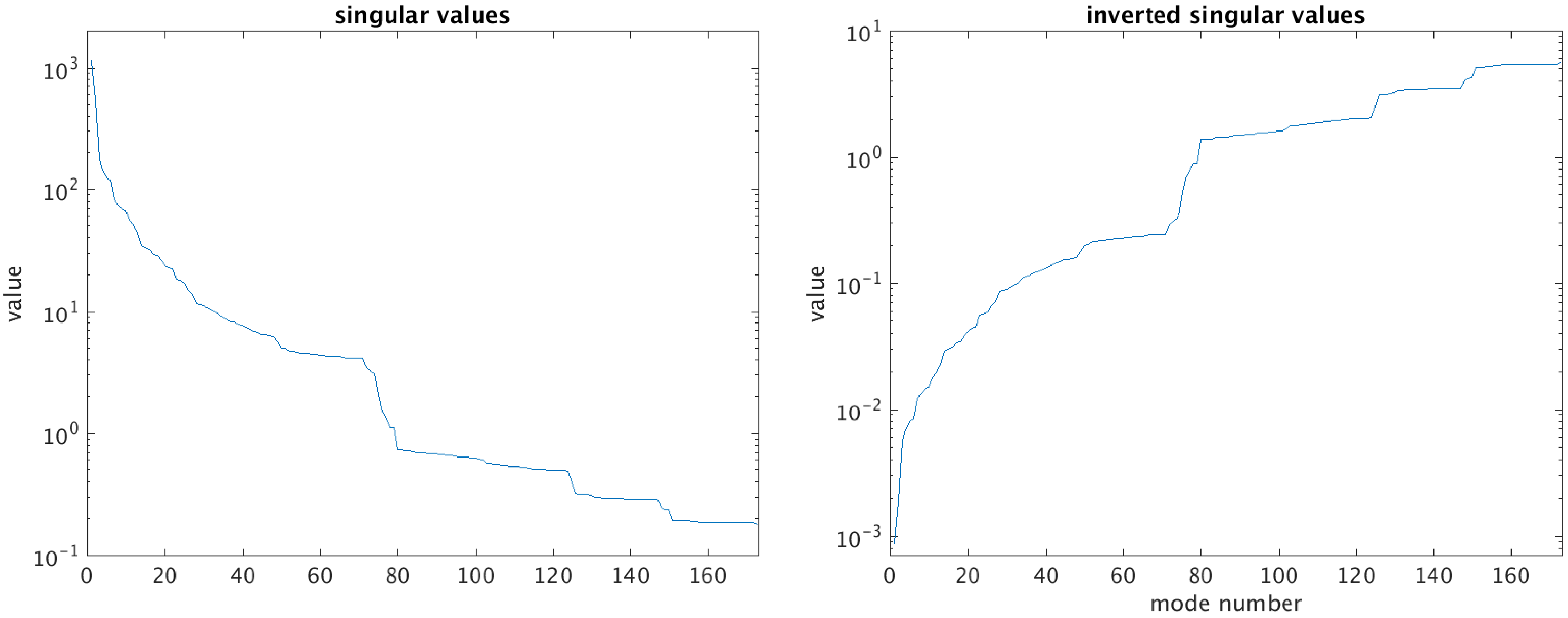
Under the hood of SVD 2





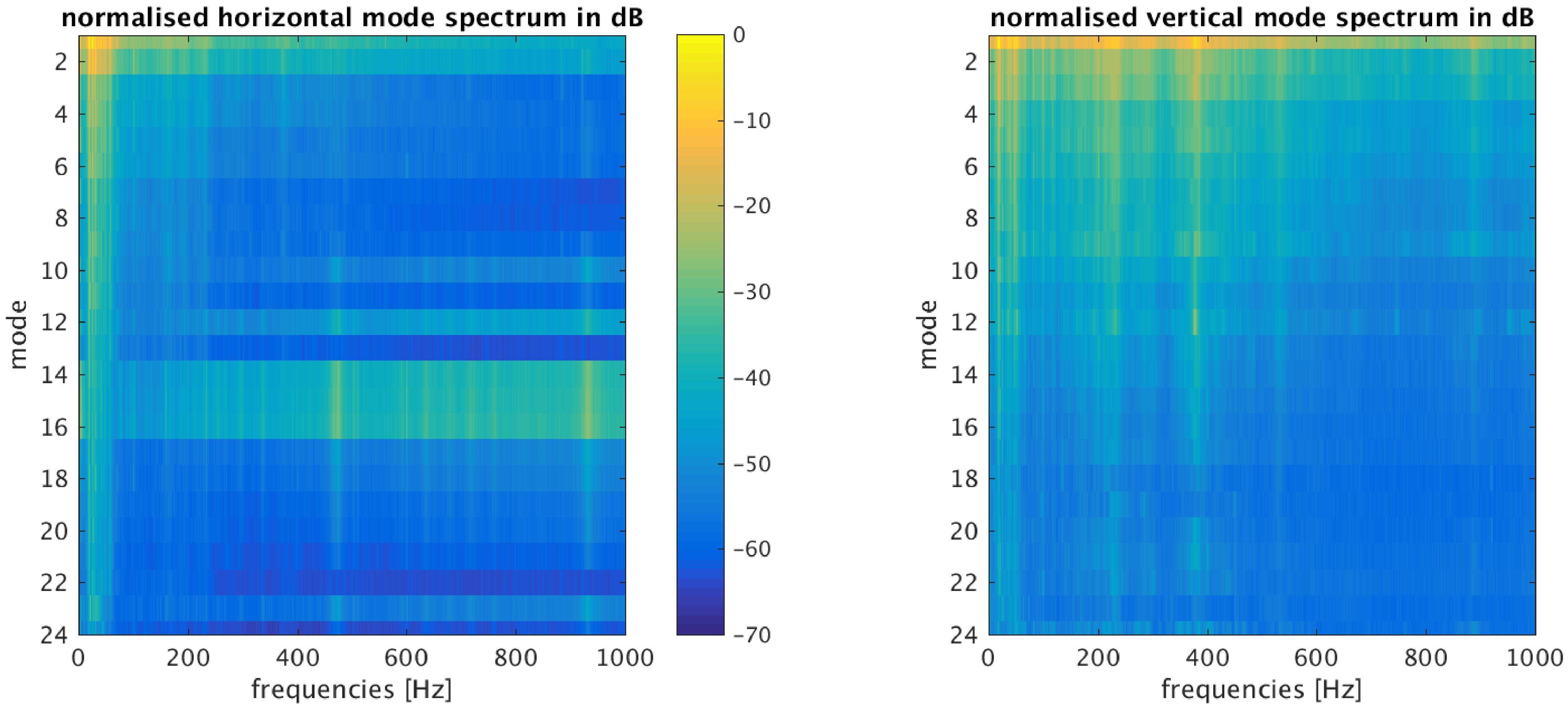
Singular Values

The singular value matrix is diagonal, so inversion simply requires inverting the individual elements
However, with poorly conditioned matrices this strongly emphasises high modes



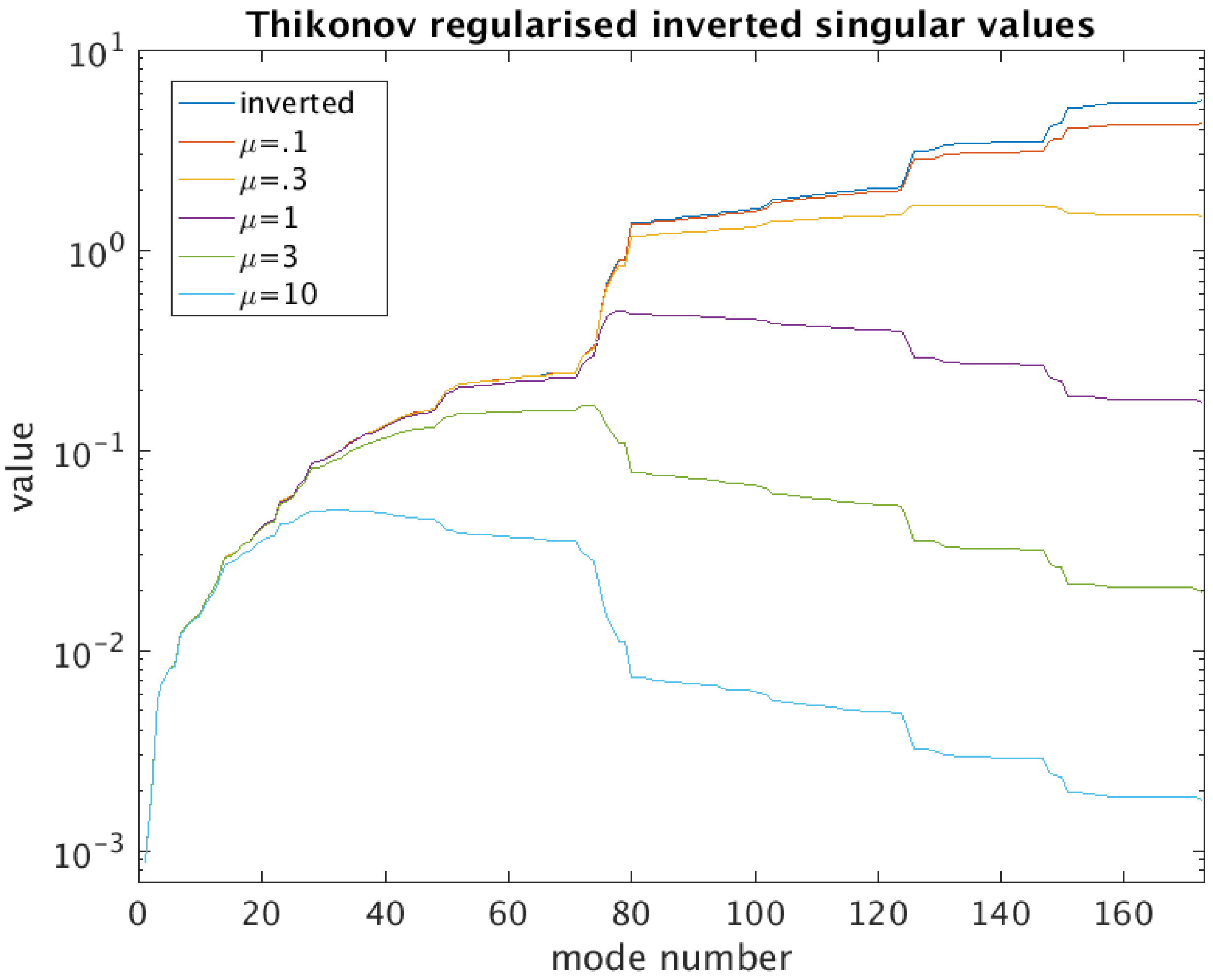
Beam Motion in Mode Space

Most orbit disturbance happens in first few modes of ORM!
Graphs below are produce from 80s (averaged over 1s FFTs) of actual whole orbit data without feedback

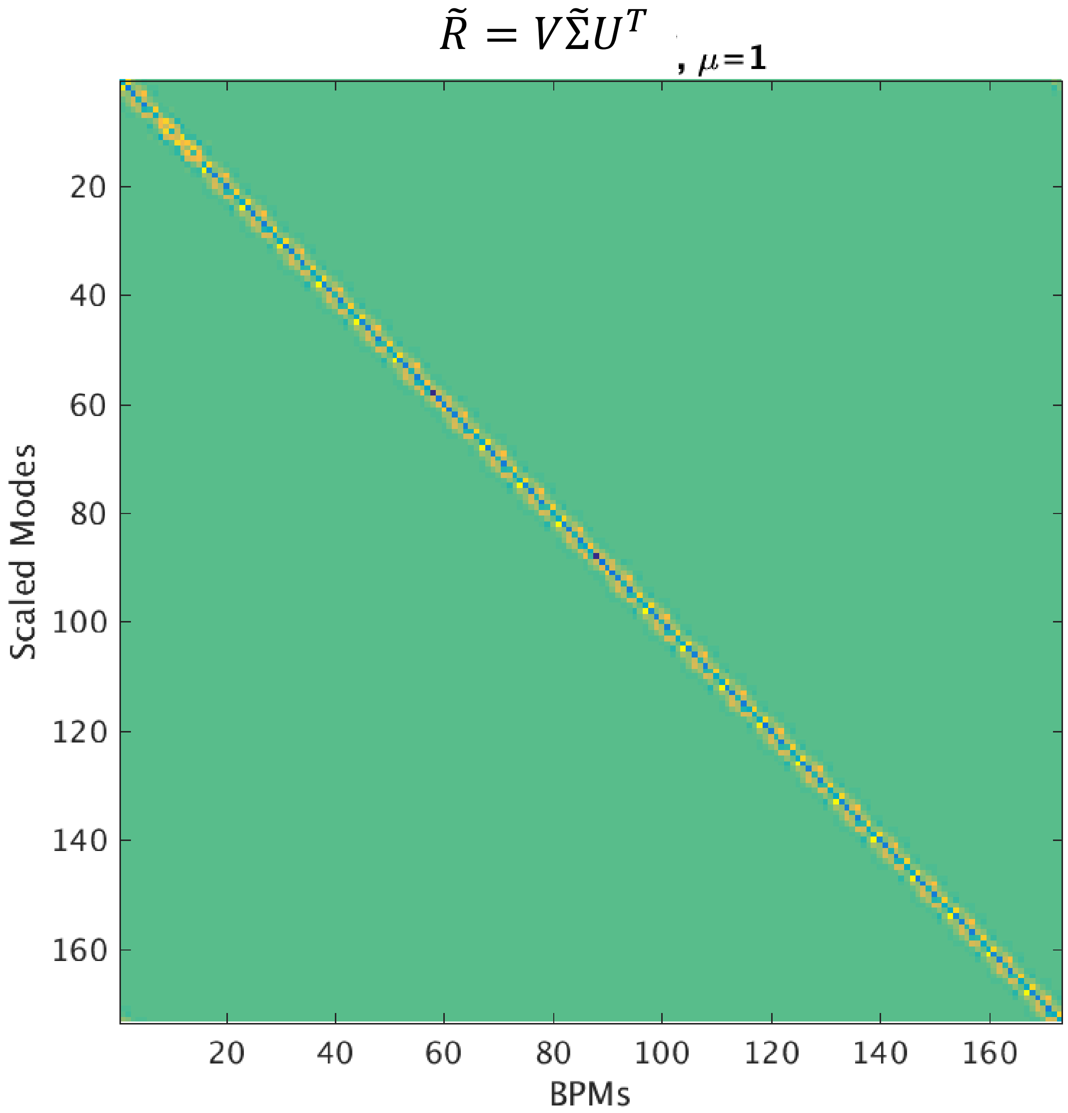


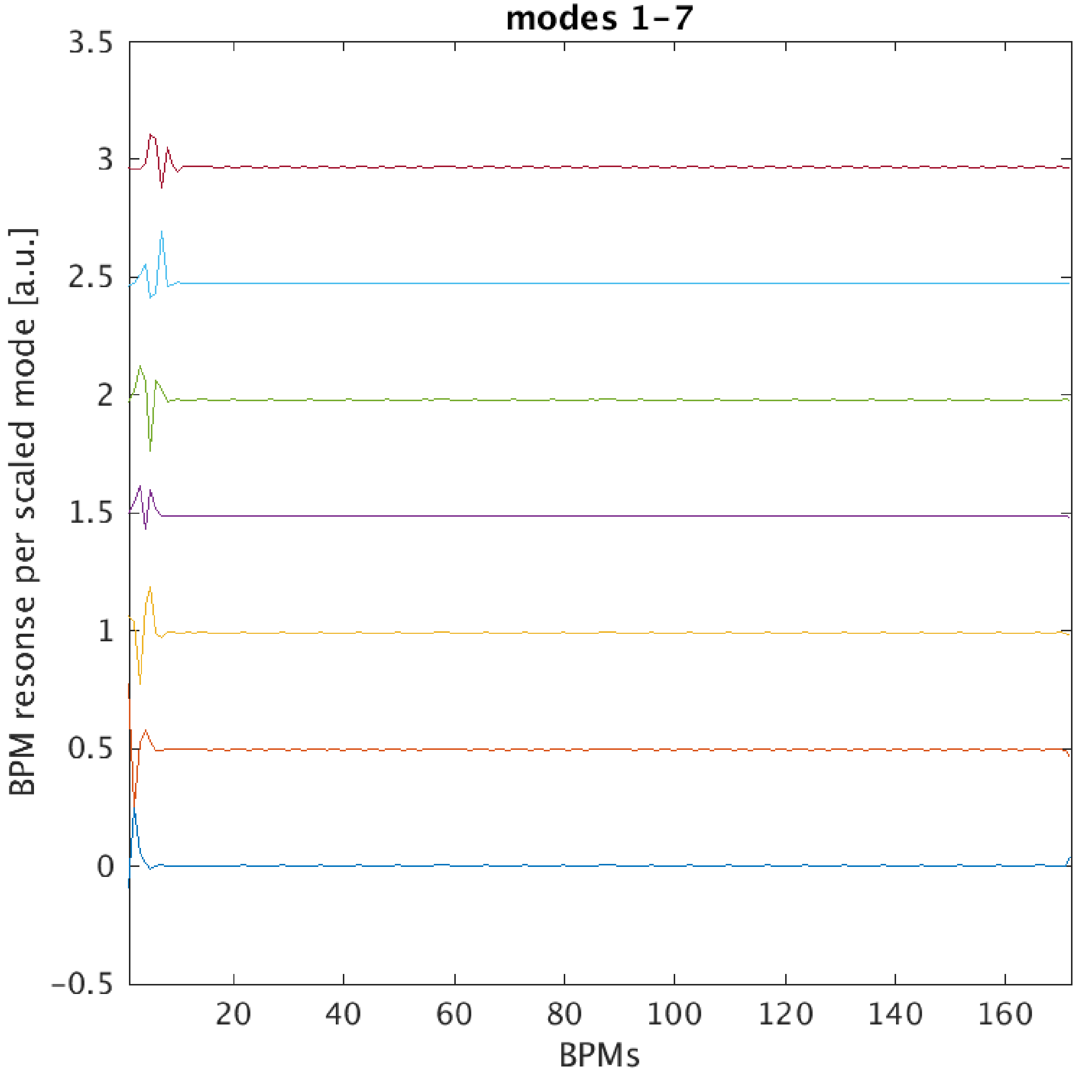
Tikhonov regularisation

- Deals with inversion of poorly conditioned matrix, less severe than culling
- Replaces inversion of singular values with $\tilde{\sigma}_{nn} = \frac{\sigma_{nn}}{\sigma_{nn}^2+\mu^2}$
- $\tilde{R} = V\tilde{\Sigma}U^T$
- Regularisation parameter μ will chose strength of ‘calming’ high modes, but they are not eliminated
- After multiple applications, the result will still be a fully corrected orbit
- With IMC controller, μ will cause lower gain for high modes
- Requires only adaptation of ORM inversion, reduces pickup of electronic noise from BPMs



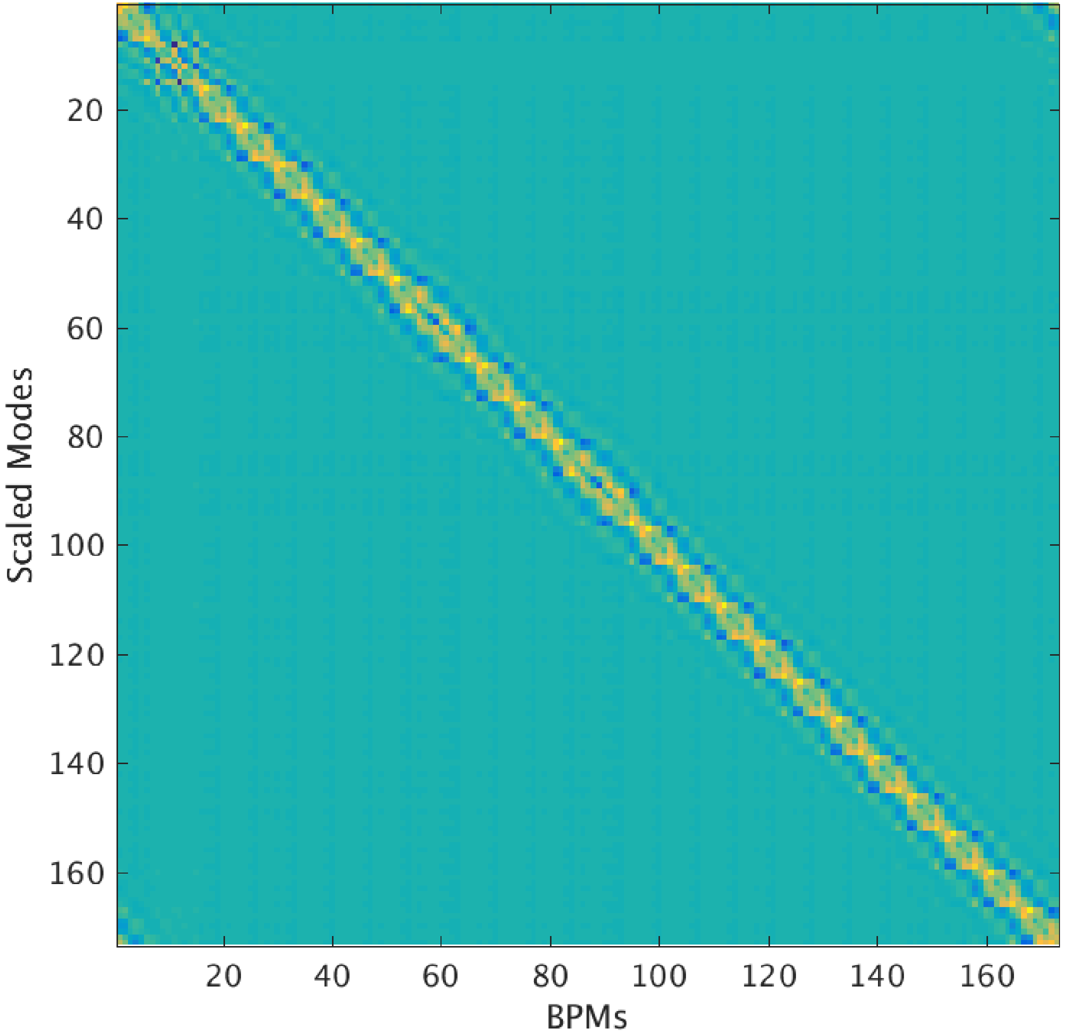
Tikhonov regularised inverted ORM, $\mu = 1$

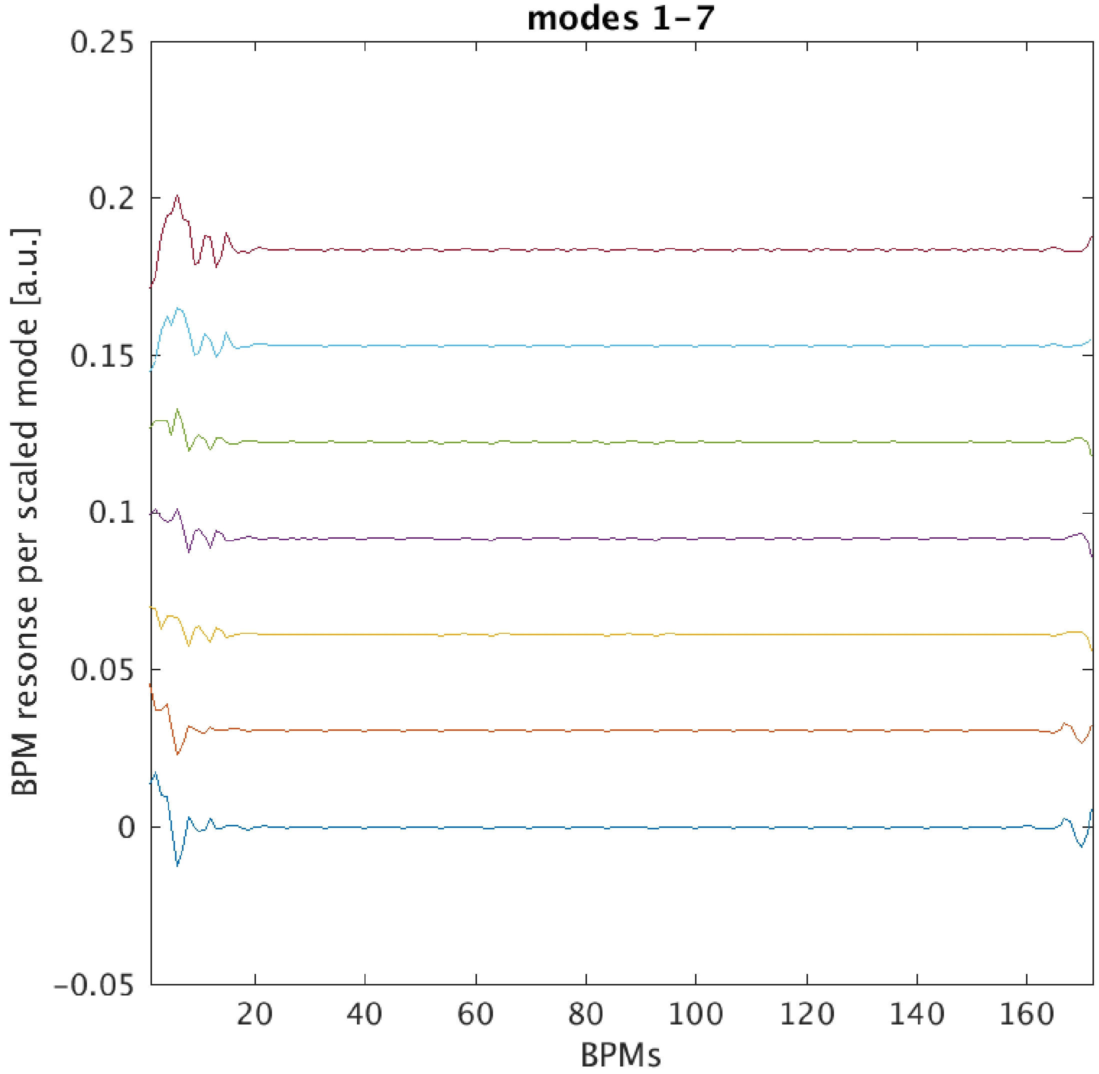




Tikhonov regularised inverted ORM, $\mu = 10$

$$\tilde{R} = V\tilde{\Sigma}U^T$$





Mode by Mode Orbit Control (MoMOC)

- Even more capable in adapting to actual orbit distortion in mode space, one controller (PID, IMC, higher order, adaptive)
- Design would choose a suitable control parameters **per mode!**
- This might be optimal control or even predictive control.
- Resulting orbit motion and required corrector action will be minimized
- Today’s commercial FOFB in use at MAX-IV, Soleil, TPS, ASLS have facilities for different PID per mode realised in FPGA!
- APS-U has presented prototype of DSP based design of similar capabilities.

How to build the ideal fast orbit feedback

- Keep tunes as close to half integer as possible
- Reduce excitation as far as possible (foundation, girders, water cooling)
- Estimate, calculate and measure bandwidth and latency of all components
- Choose fastest transport network on the market (10+Gb/s)
- Choose BPMs with high sample rate (100-200kS/s, or turn-by-turn)
- Bring all data to one compute node with enough power
- If it saves much time, repeat computations in many locations
- Implement modern control on DSP or FPGA, keep maintenance in mind
- Distribute corrector data through same or similar network
- Use power convertors designed, built and tested for bandwidth and low latency
- Use fast corrector magnets (laminated or ferrite) over thin, low conductivity vessels (thin stainless or Inconel) to reduce eddy currents
- If not all correctors can be fast, modern control algorithms can deal with that in one calculation
- Finally, low synchrotron frequency might cause interaction with RF cavity feedback!

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Announcement

Topical Workshop on Diagnostics for Ultra Low Emittance Rings (TW-DULER)

Supported by the **ARIES** European project, under the Ring with Ultra Low Emittance (**RULE**) work package coordination:

Synchrotron SOLEIL and **Diamond Light Source** are organizing a:

Topical Workshop on
Diagnostics for Ultra Low Emittance Rings
19-20 April 2018
Diamond Light Source

Scientific Program Committee:

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