Identification of Intra-Bunch Transverse Dynamics for Model Based Wideband Feedback Control at CERN Super Proton Synchrotron

O. Turgut[1], J. Dusatko[1], J. Fox[1], C. Rivetta[1], W. Hofle[2], K. Li[2], G. Kotzian[2], U. Wehrle[2], A. Drago[3]

[1]SLAC National Accelerator Laboratory
[2]CERN
[3]INFN-LNF

May 11, 2015

Supported by the U.S. DOE under contract DE-AC02-76SF00515 and the US LARP

Outline

- Introduction
- Intra-Bunch Dynamics Identification
  - SPS Measurements
  - Nonlinear Macro Particle Simulation Data
- Model Based Controller Efforts
- Future work and directions

Introduction

- Multi-input multi-output (MIMO) feedback design techniques can be helpful to stabilize intra-bunch transverse instabilities induced by electron-clouds or transverse mode couplings at the CERN Super Proton Synchrotron (SPS).
- These MIMO techniques require a reduced order model of intra-bunch dynamics.
- We present linear reduced order MIMO models for transverse intra-bunch dynamics and use these models to design model based MIMO feedback controllers.
- The effort is motivated by the plans to increase currents in the SPS as part of the HL-LHC upgrade.

Reduced Order Model Representations - Example

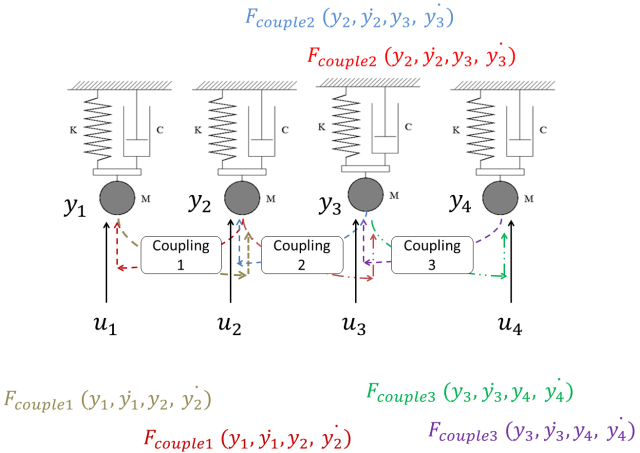


Figure : 4 x 4 MIMO Representation of the Intra-Bunch Dynamics

- Higher order dynamics can be analyzed by extending the model up to N coupled harmonic oscillators.
- For example, the model above can capture up to 4 modes.

Formalism and Parameter Estimation

$$X_{k+1} = AX_k + BU_k \quad Y_k = CX_k \tag{1}$$

$$Y(z) = \left[D^{-1}(z)N(z)\right]U(z) \tag{2}$$

$$N(z)U(z) - D(z)Y(z) = 0 \tag{3}$$

$$U(z) = \sum_{i=0}^{T} U_i z^i, \quad Y(z) = \sum_{i=0}^{T} Y_i z^i \tag{4}$$

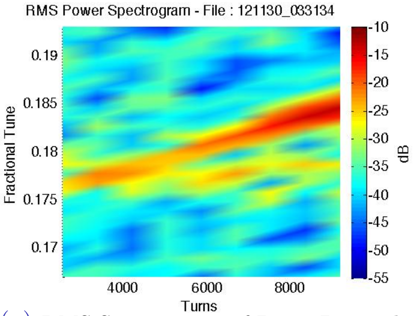
$$D(z) = \sum_{i=0}^{m} D_i z^i, \quad N(z) = \sum_{i=0}^{n} N_i z^i \tag{5}$$

$$\left[N_r \mid - D_r\right] \begin{bmatrix} U(k) \\ Y(k) \end{bmatrix} = 0 \tag{6}$$

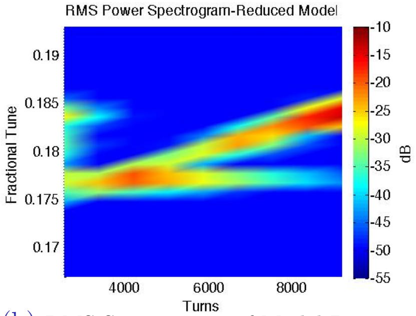
- where $U \in R^p$ is the control variable, $Y \in R^q$ is the vertical displacement measurement, $A \in R^{n \times n}$ isystem matrix, $B \in R^{n \times p}$ input matrix, and $C \in R^{q \times n}$ output matrix.
- [] represents the transfer function matrix ($\in R^{q \times p}$) for a system with p inputs and q outputs. $D(z)$ and $N(z)$ represent denominator and numerator of discrete time transfer function matrix between input-output couples.
- The estimation of the parameter matrices N_r and D_r is obtained by solving the last linear equation using time domain data.

Comparison of Measurements with Reduced Model

- Driven chirp SPS measurement spectrogram (left), reduced model spectrogram (right)
- Chirp tune 0.175 - 0.195 turns 2K - 17K
- Tune 0.177 barycentric mode, tune 0.183 (first upper synchrotron sideband)
- Model and measurement agreement suggests dynamics can be closely estimated.



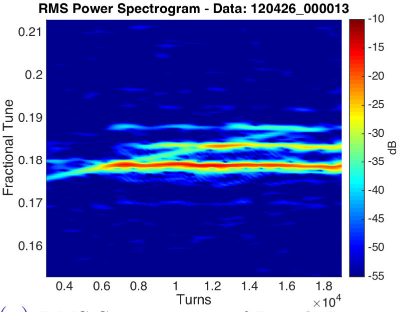
(a) RMS Spectrogram of Beam Driven by 200 MHz Chirp Excitation Sequence



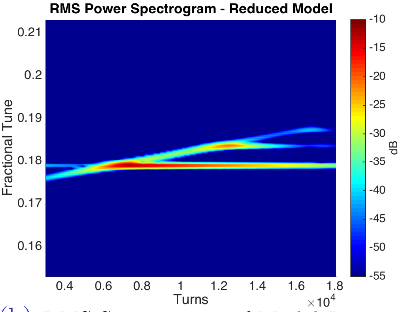
(b) RMS Spectrogram of Model Driven by 200 MHz Chirp Excitation Sequence

Exciting Mode 0, 1^{st} and 2^{nd} Upper Side Bands

- A specific machine condition with very low chromaticity configuration.
- As expected, our linear model is able to capture dominant characteristics and linear dynamics such as motions at mode 0, mode 1 and mode 2 tunes, but not the effect attributed to the non-linearities in the bunch.
- Robustness of the identification algorithm has to be analyzed for such machine conditions.



(a) RMS Spectrogram of Bunch Driven by 200 MHz Chirp Excitation



(b) RMS Spectrogram of Model Driven by 200 MHz Chirp Excitation

Reduced Model Validation with SPS Measurements

- We did growth/damp measurements using destabilizing and stabilizing FIR filters in closed loop.
- We extract growth and damping rates from these measurements.
- We use these values as reference to validate our reduced order model accuracy.

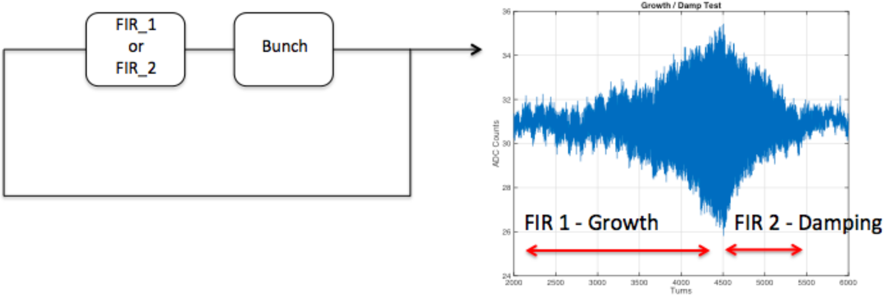
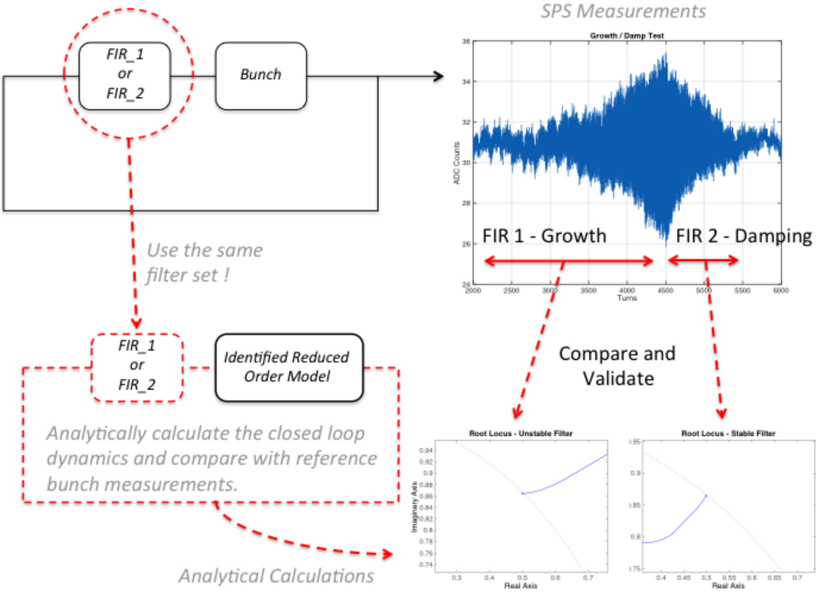


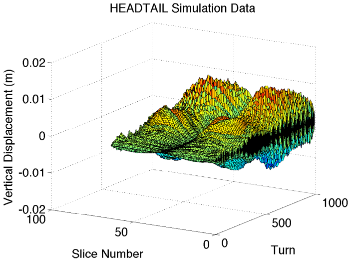
Figure : Drive the bunch unstable using destabilizing phase in FIR filter and then use stabilizing FIR phase to damp the motion.

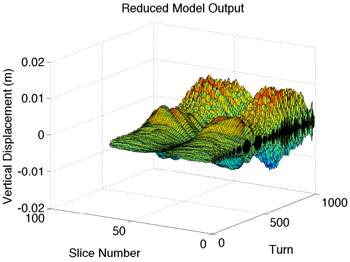
Reduced Model Validation with SPS Measurements

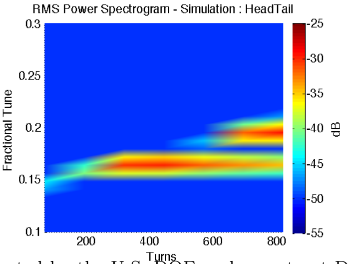


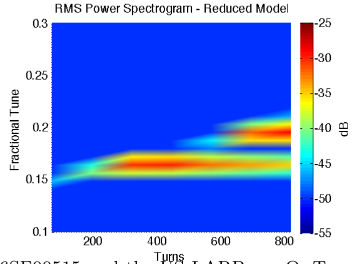
Comparison of HEADTAIL with Reduced Model

- Figures on top show vertical motion of bunch, driven by 200 MHZ, 0.144 - 0.22 Chirp, 1000 Turns. Bottom figures are corresponding spectrograms.









HEADTAIL Dominant Dynamics / Model Reduction

- If we look at the Henkel Singular Value analysis, we can realize that 8 or 14 states (4 or 7 modes) out of >128 states are main contributors to the dynamics. Therefore we should be able to fit an 8th / 14th order model to capture these dynamics. Rest should be redundant.

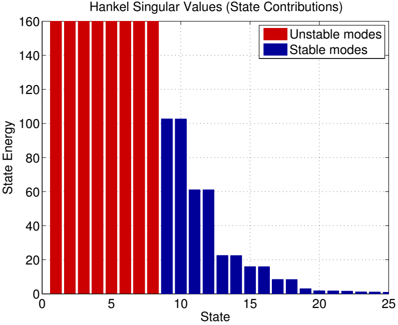
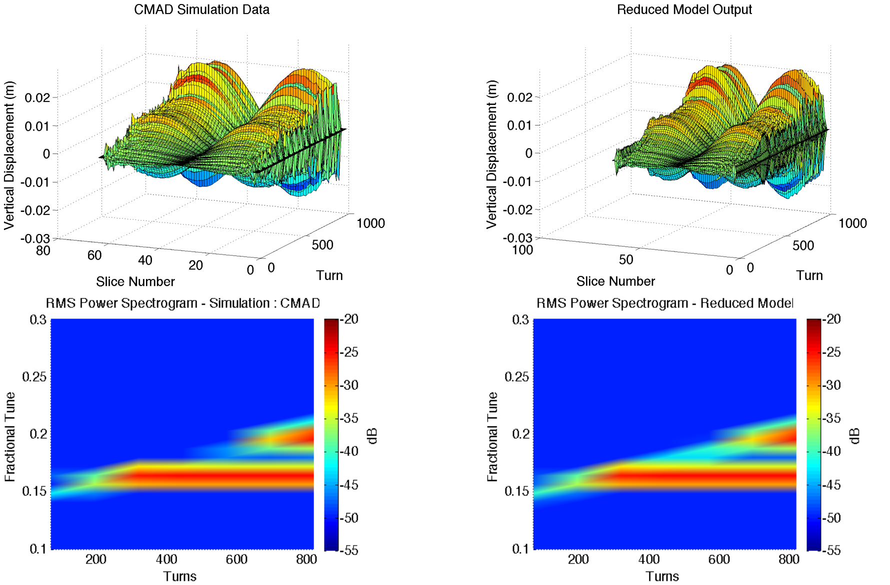


Figure : Henkel Singular Values Analysis - 4 Dominant Modes

Table : Dominant Modes, Synchrotron Tune 0.017

Mode	Eigenvalue
1	$\pm 0.1800i$
2	$\pm 0.1632i$
3	$\pm 0.1959i$

Comparison of CMAD with Reduced Model



CMAD Dominant Dynamics / Model Reduction

- If we look at the Henkel Singular Value analysis, we can realize that 6 states (3 modes) out of >128 states are main contributors to the dynamics. Therefore we should be able to fit a 6th order model to capture these dynamics. Rest should be redundant. Notice the small differences between CMAD and HeadTail eigenvalues.

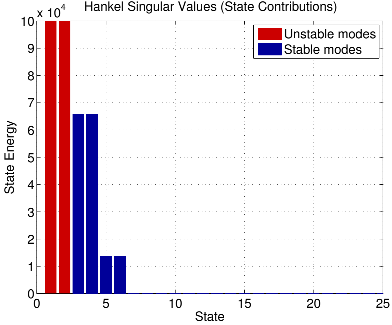
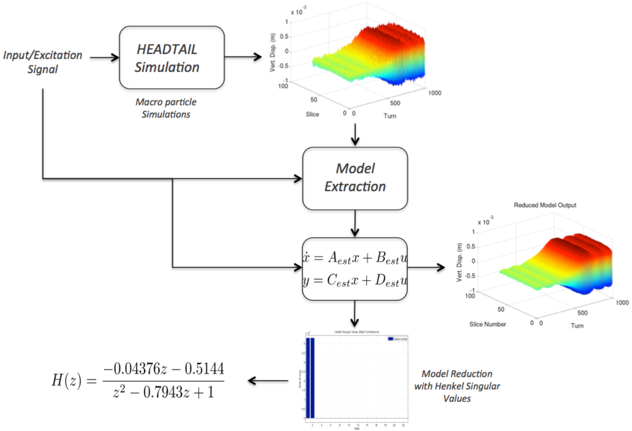


Figure : Henkel Singular Values Analysis - 3 Dominant Modes

Table : Dominant Modes, Synchrotron Tune 0.017

Mode	Eigenvalue
1	$\pm 0.180i$
2	$\pm 0.163i$
3	$\pm 0.197i$

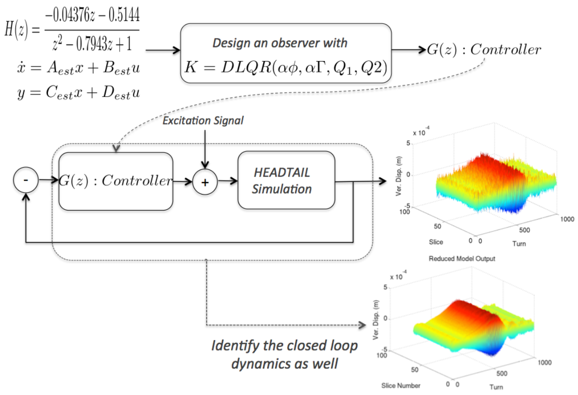
Reduced Model from Open Loop Simulations



- Parameters of the transfer function representing the mode 0 dynamics are identified using open loop simulation data.
- We use the same excitation signal to drive the reduced order model and compare the time domain result with HeadTail simulation result for model verification.
- This model (mode 0 dynamics) is used to design a model based controller (Discrete Linear Quadratic Regulator Methods - Next Slide).

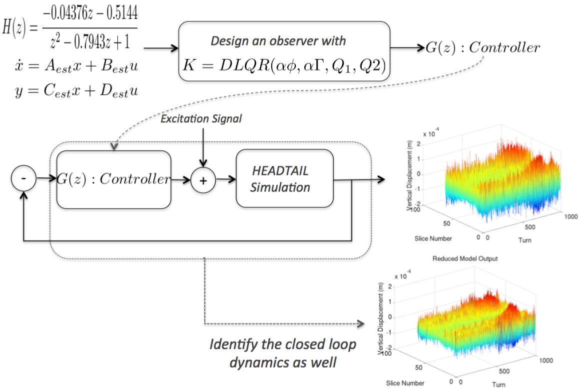
Supported by the U.S. DOE under contract DE-AC02-76SF00515 and the US LARP

Model Based Controller - Closed Loop (Mode 0) Simulations



- An observer based controller (DLQR and Pole Placement) is designed using the identified reduced model.
- Closed loop dynamics can be analytically estimated. These analytical calculations can also be validated by identification of closed loop dynamics from feedback on HeadTail simulation data.
- Simulation results clearly show damping in time domain too when compared with open loop data.

Model Based Controller - Closed Loop (Mode 1) Simulations



- We study the effect of model based controller (designed for mode 0 dynamics) on mode 1 dynamics.
- Similarly the closed loop dynamics can be analytically estimated for mode 1 and validate the results using nonlinear macro particle simulation codes.
- We observe damping in mode 1 dynamics and compare the performance of a model based with an FIR filter in next slide.

FIR vs Model Based - Initial Resutls

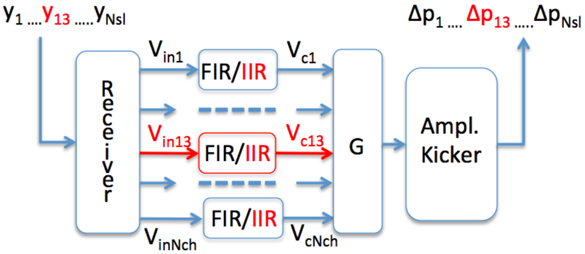


Figure : Diagonal Controller Architecture in HeadTail - FIR vs IIR, Coutesy: Claudio Rivetta

		Model Based IIR	*5 Tap FIR*
Open Loop Dynamics	Mode 0	$-0.000 \pm 0.185i$	
Closed Loop Dynamics	Mode 0	$-0.0074 \pm 0.183i$	$-0.0074 \pm 0.185i$
	Mode 1	$-0.0037 \pm 0.199i$	$-0.0026 \pm 0.2i$

Conclusion and Future Work

- Estimation of reduced order model parameters based from SPS MD measurements and nonlinear macro particle simulation data show promising results.
- Reduced order models can successfully capture linear dominant dynamics.
- Initial model based controller efforts show these models can be used in controller design.
- However this study requires some future work including:
    - Verification of SPS measurements based on reduced order models using open/closed loop 2014-2015 MDs.
    - Design, analysis and implementation of MIMO non diagonal controller architectures in HeadTail Nonlinear Macro Particle Simulation
    - Feasibility of Implementation of model based controller architecture in FPGA.
    - Test and demonstrate the model based controller for single bunch in SPS.