Identification of Intra-Bunch Dynamics using MD Measurements and Macro Particle Codes [1]

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Reduced Order Model Parameter Identification

- The ultimate goal is to stabilize Ecloud and TMCI effects using wide-band intra-bunch feedback system.
- Controlling multiple locations across the bunch requires multi-input multi-output (MIMO) analysis.
  - Important ! For example, you can make higher modes unstable while trying to control dipole mode. (Seen case in HEADTAIL simulations !)
- The goal of identification is to fit parameters of the reduced order MIMO model using MD measurements and macro-particle simulation codes.
- Reduced order model is required to design a smart control architecture to stabilize effects of disturbances on intra-bunch dynamics under hardware and processing power constraints.

Model and Formalism

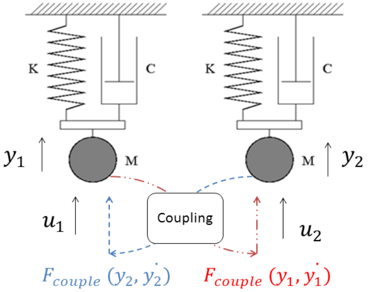


Figure : Reduced Model for Dipole and Head -Tail Modes

$$\mathbf{y}(z) = \hat{\mathbf{D}}(z)^{-1}\hat{\mathbf{N}}(z)\mathbf{u}(z)$$

$$\mathbf{u}(z) = \sum_{i=0}^{\infty} \mathbf{u}_i z^{-i}; \quad \mathbf{y}(z) = \sum_{i=0}^{\infty} \mathbf{y}_i z^{-i}$$

$$\hat{\mathbf{D}}(z) = \sum_{i=0}^{k} \mathbf{D}_i z^{i}; \quad \hat{\mathbf{N}}(z) = \sum_{i=0}^{k} \mathbf{N}_i z^{i}$$

$$\mathbf{D}_k = \mathbf{I}_p$$

$$\mathbf{Q}_o = [\mathbf{C}^T | \mathbf{A}^T\mathbf{C}^T | \cdots | (\mathbf{A}^T)^{k-1}\mathbf{C}^T]^T$$

$$\rho[\mathbf{Q}_o] = n = k * p$$

$$\mathbf{A} = \begin{bmatrix} \mathbf{O} & \mathbf{O} & \cdots & \mathbf{O} & -\mathbf{D}_0 \\ \mathbf{I}_p & \mathbf{O} & \cdots & \mathbf{O} & -\mathbf{D}_1 \\ \mathbf{O} & \mathbf{I}_p & \cdots & \mathbf{O} & -\mathbf{D}_2 \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ \mathbf{O} & \mathbf{O} & \cdots & \mathbf{I}_p & -\mathbf{D}_{k-1} \end{bmatrix}$$

$$\mathbf{B} = \begin{bmatrix} \mathbf{N}_0 - \mathbf{D}_0\mathbf{N}_k \\ \mathbf{N}_1 - \mathbf{D}_1\mathbf{N}_k \\ \mathbf{N}_2 - \mathbf{D}_2\mathbf{N}_k \\ \vdots \\ \mathbf{N}_{k-1} - \mathbf{D}_{k-1}\mathbf{N}_k \end{bmatrix}$$

$$\mathbf{C} = [\mathbf{O} \;\; \mathbf{O} \;\; \cdots \;\; \mathbf{O} \;\; \mathbf{I}_p]; \quad \mathbf{D} = \mathbf{N}_k$$

Figure : Observable Canonical Form for Discrete Time MIMO System

$$\begin{aligned} X_{k+1} &= AX_k + BU_k \\ Y_k &= CX_k \end{aligned} \qquad (1)$$

where control variable (external excitation) $U \in R^p$, vertical displacement measurements $Y \in R^q$, system matrix $A \in R^{n \times n}$, input matrix $B \in R^{n \times p}$, and output matrix $C \in R^{q \times n}$.

Extension of the Reduced Order Model

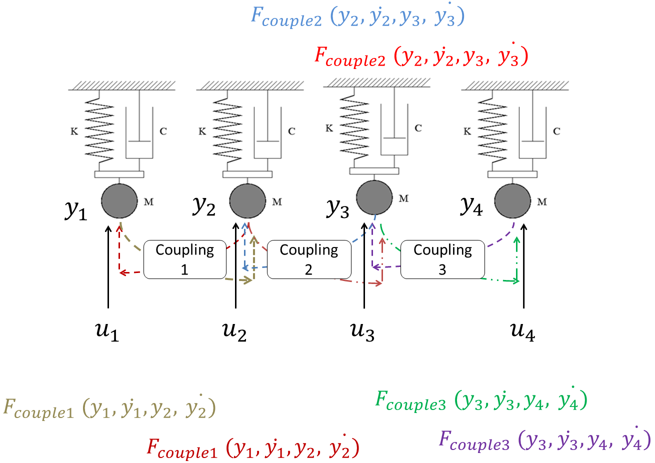


Figure : 4 x 4 MIMO Representation of the Intra-Bunch Dynamics

- 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.

Data for Identification

- Experimental data was collected from a single bunch with 1×10^{11} protons at 26 GeV with low chromaticity configuration at CERN SPS.
- Both open loop driven and closed loop feedback measurements were taken. Main focus is on open loop driven measurements for identification in this presentation.
- In analysis, we use data from April, November, December 2012 and January, February 2013 MDs together with CMAD and HEADTAIL simulations.

Arranging Input and Output Data

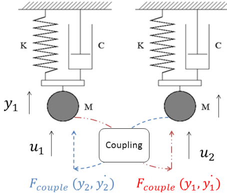


Figure : 2 x 2 Representation. Measured data should be arranged in such a way that we have 2 inputs 2 outputs.

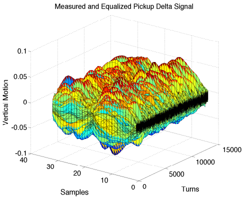


Figure : Example of measured and equalized pick-up signal. Number of samples across the bunch changes with sampling rate.

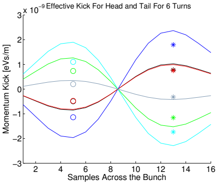


Figure : The effective kick for the head and the tail is calculated by averaging the momentum waveform between samples 1-8 and 9-16. Average kicks, o : head, $*$: tail.

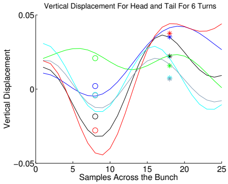


Figure : Effective displacements are calculated by averaging the vertical displacement waveform between samples 1-12 and 13-25. Average, o : head, $*$: tail.

MD Measurements - 2 x 2 Model

- Drive SPS bunch using frequency chirp excitation signal and record corresponding vertical motion.
- Based on the transfer functions of cable plant, amplifiers and kicker, we calculate the momentum kick that beam goes through.
- Using the momentum kick signal and vertical displacement measurement, estimate the parameters of reduced order model.
- Drive the reduced order model with the same momentum kick signal to get vertical motion that model estimates.

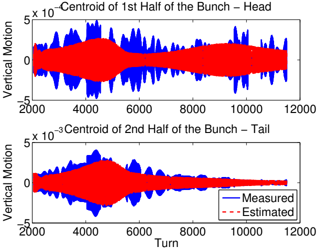


Figure : Comparison between the measured vertical motion of the head and the tail with model's response.

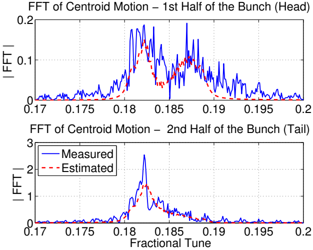


Figure : The FFT's of measured vertical motion of the head and the tail together with model's response.

MD Measurements - 4 x 4 Model, In Time Domain

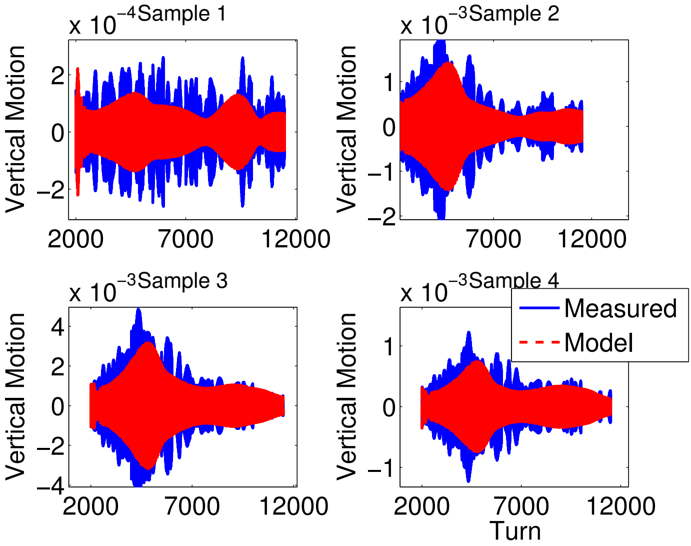


Figure : Vertical Motion at Four Different Locations Across the Bunch. Blue: Masurement, Red: Reduced Model Outputs

MD Measurements - 4 x 4 Model, In Freq. Domain

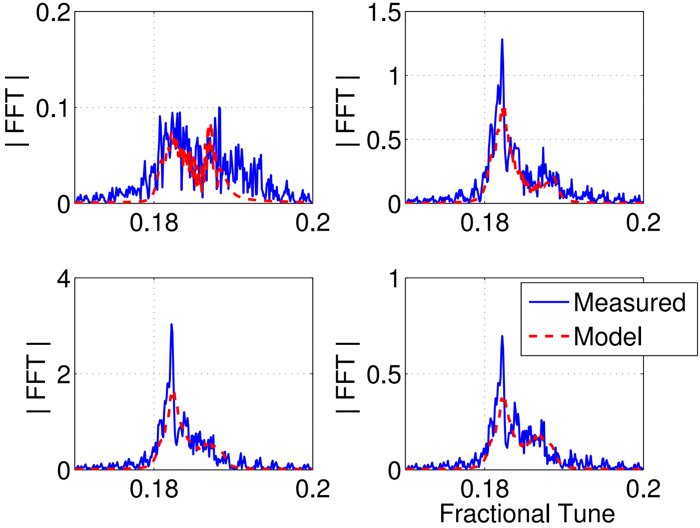


Figure : FFT Analysis of Vertical Motion for Four Regions Across the Bunch. Blue: Masurement, Red: Reduced Model Outputs

Different MD Measurement, In Freq. Domain

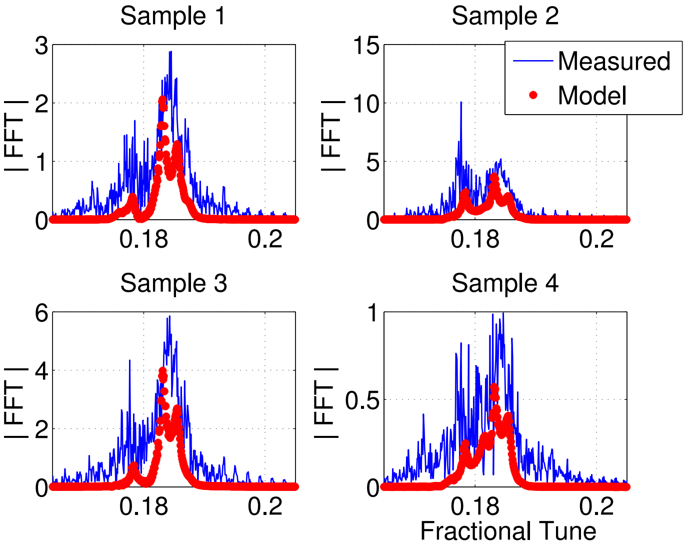


Figure : FFT Analysis of Vertical Motion for Four Regions Across the Bunch. Blue: Masurement, Red: Reduced Model Outputs

Modal Decomposition in Time Domain

- Motion starts with relatively small mode 0, as chirp frequency approaches the first side band, head-tail mode gets excited, right after head-tail around turn 10000, we see some motion in 2nd side-band. Is this true ?

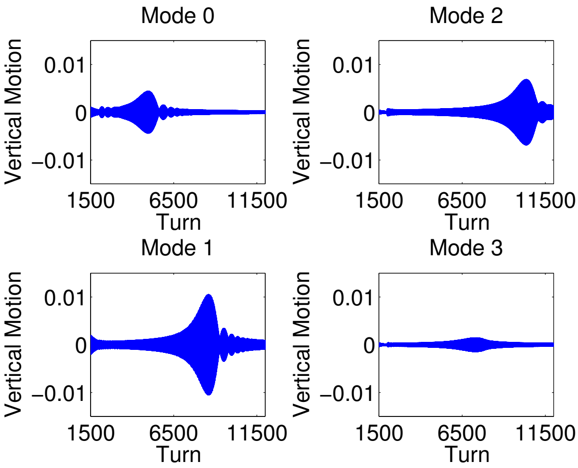
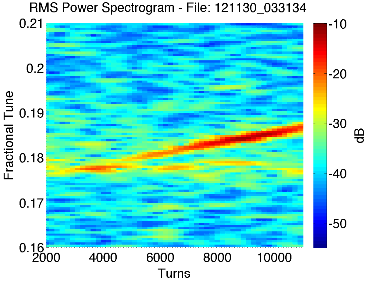


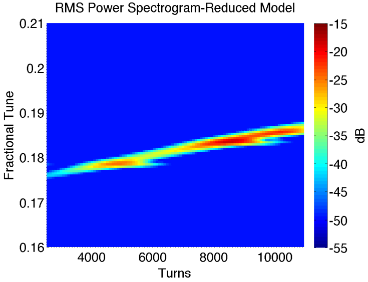
Figure : Vertical motion is decomposed into modal form.

Spectorgram Comparison

- If we look at the spectorgram of the measured data, between turns 8000 and 10000 we see two clear peaks, which are not seperated by synchrotron tune. One possible explanation is that tune is wondering and that is captured with identification.



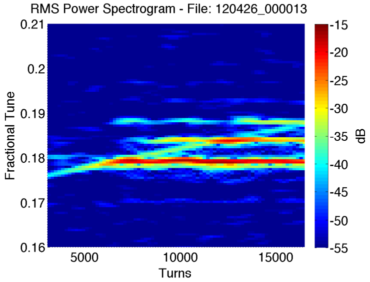
(a) RMS Spectrogram of Beam Measurement Driven by 200 MHz Chirp Excitation



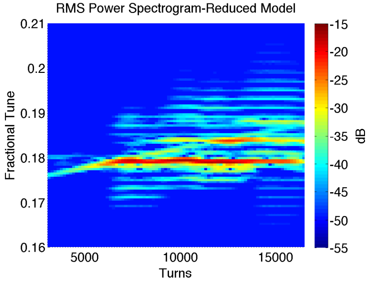
(b) RMS Spectrogram of Model's Output Driven by Same 200 MHz Chirp Excitation

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

- A specific machine condition with very low chromaticity configuration.
- Agreement between measurement and model shows that reduced order model can capture dynamics.
- Robustness of the identification algorithm has to be analyzed for such machine conditions.



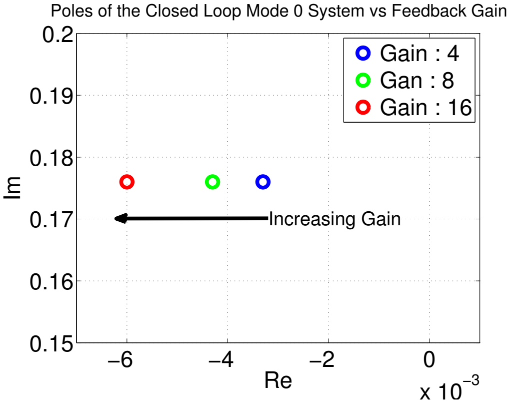
(a) RMS Spectrogram of Beam Measurement Driven by 200 MHz Chirp Excitation



(b) RMS Spectrogram of Model's Output Driven by Same 200 MHz Chirp Excitation

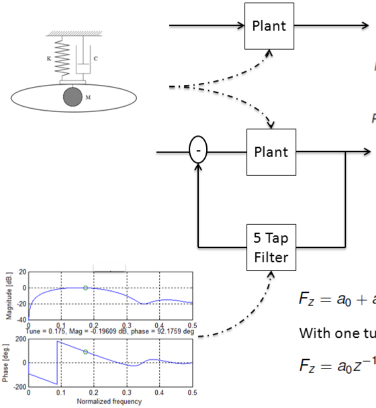
Closed Loop Measurement Analysis

- System identification is also applicable to closed loop data.
- Using externally driven closed loop feedback measurements for three different gain for the same filter configuration, three different reduced mode and the corresponding poles are estimated.
- Identification captures the effect of the feedback on mode 0 dynamics for different gain levels.



Identification in Simulation Studies

- Let's look at a simple example in CMAD and think about where identification studies can lead to.
- Bunch is represented by a centroid. Using the exact same filter we used in MDs, close the loop on bunch while driving it with an external frequency chirp excitation.



$$P(s) = \frac{\omega_n^2}{s^2 + 2\zeta\omega_n s + \omega_n^2}, \zeta \approx 0, \omega_n = 0.185, \lambda = \pm 1.1624i$$

$$P(z) = \frac{0.4386z}{z^2 - 0.7943z + 1}, \lambda_d = 0.3971 \pm 0.9177i$$

$$F_z = a_0 + a_1 z^{-1} + a_2 z^{-2} + a_3 z^{-3} + a_4 z^{-4}$$

With one turn delay:

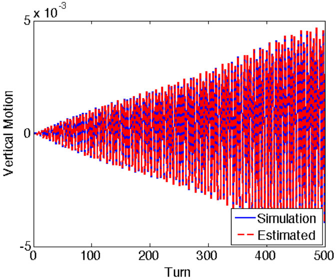
$$F_z = a_0 z^{-1} + a_1 z^{-2} + a_2 z^{-3} + a_3 z^{-4} + a_4 z^{-5}$$

Figure : Open and closed loop driven simulation for mode 0 dynamics analysis.

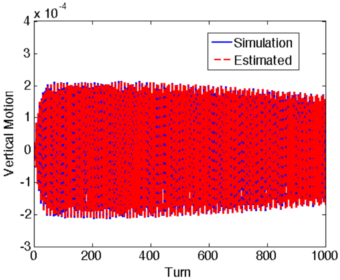
System Identification Results

- 5 tap filter $\rightarrow$ 7th order closed loop system. Reduced order model and identification techniques identify the dominant dynamics.

$$\begin{aligned} \lambda_{closedLoop} &= -0.0692 \pm 1.1456i, -0.755 \pm 0.97i, \ldots \\ \lambda_{estimated} &= -0.0683 \pm 1.1459i \end{aligned} \quad (2)$$



(a) Vertical displacement of the driven system in open loop.



(b) Vertical displacement of the closed loop driven system.

Very Useful Tool for Macro Particle Simulations ?

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- As seen in previous slide, using a reduced order model we can identify a closed loop simulation with a certain control filter and gain.
- Here is my short term plan :
  - Claudio Rivetta and I are trying to get a local version of HeadTail running at SLAC in colloboration with Kevin Li at CERN.
  - I can run my identification on Head -Tail Simulation data where we drive an open loop case.
  - With the help of reduced order model and a controller that we specify, I should be able to help Kevin to decide exaclty what gain to use to stabilize a desired mode without making others unstable without trying all possible gains in the gain space.

Why System Identification and Reduced Order Model

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- Beam Diagnostics Tool
  - Beam parameters can be measured during MD such as modes, tunes,etc. . .
- Required for Controller Design
  - Enables us to use control design techniques.
  - Powerful solution to study different kinds of control techniques, i.e. optimal control, robust control, without using too much machine time.
  - Applicable to machine measurements together with simulation data (HeadTail/CMAD).
  - Validation tool for simulations using machine measurements or vice-versa.
  - Allows us to predict the future behavior of the system exploring wide parameter space as opposed to running simulations for each unique condition. For example, predicting the minimum gain to stabilize as opposed to running simulation for different gains until finding a stabilizing gain.

Thank you for your attention !

- Any questions ? . . .