IDENTIFICATION OF BUNCH DYNAMICS IN THE PRESENCE OF E-CLOUD AND TMCI FOR THE CERN SPS RING *

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Abstract

We present a methodology to identify single bunch dynamics in the presence of electron cloud (e-cloud) and head-tail interaction in the CERN SPS ring. The main purpose is to extract the bunch dynamics from measurements and to estimate a reduced mathematical model of vertical dynamics. This reduced model is useful in the design of wide-band feedback systems to control/stabilize the bunch in the presence of e-cloud and transverse mode coupling instabilities (TMCI). The system estimation method is applied to data from numerical simulations as well as machine measurements from the SPS MD data. We illustrate this with examples from initial applications of the identification technique and present the beam excitation and response measurement hardware set-up, with future directions and next MD plans.

INTRODUCTION AND MOTIVATION

The SPS at high intensities exhibits transverse single-bunch instabilities with signatures consistent with transverse mode coupling and e-cloud driven instabilities [1] [2] [3] [4]. A high frequency feedback system is a promising approach to control transverse bunch instabilities induced not only by e-cloud but also induced by transverse mode coupling instabilities anticipated for high current in SPS and LHC operations [5]. The application of feedback control to stabilize the bunch is challenging because it requires a bandwidth sufficient to sense the transverse position and apply correcting fields to multiple sections of a nanosecond-scale bunch.

Feedback system design is intrinsically associated with the knowledge of the dynamic behavior of the system to control / stabilize. Reduced mathematical models are used to characterize the system dynamics and define a framework to design the control system. In particular, the model characterizing the bunch dynamics has to capture in a simple form the motion of a large amount of particles within the bunch. These models can be data-driven or first principles based, where the former technique requires system identification tools to fit the acquired and processed data to a mathematical model. The *model-based design technique* addresses problems associated with design of complex control systems and provides an efficient approach to quantify stability margins of the system, impact of external perturbations, uncertainties and parameter variations of the

system, etc.

Identification techniques are based on driving the dynamic system by injecting an input signal with enough frequency content to excite all the dominant natural modes of the system and measuring the time response or output signal. Based on the measured input/output signal, a reduced model that represents the bunch dynamics is fitted to the data collected. To extend this identification process to model the bunch dynamics we follow two converging paths. One of them is focused on the developing wideband excitation hardware and beam instrumentation to study intra-bunch motion. The other concerns developing identification techniques to define reduced mathematical models that represent the dominant dynamics of the bunch when it is perturbed by e-clouds or strong head-tail interaction. Ultimately, the goal is to be able to define reduced mathematical models representing the bunch dynamics to design feedback control systems to mitigate intra-bunch instabilities. These methods offer non-invasive techniques to estimate beam and machine parameters. In this paper, we present progress and preliminary results in both areas.

SYSTEM IDENTIFICATION : BASIC CONCEPTS

System identification uses statistical methods to build mathematical models of dynamical systems from observed input and output data [8]. Fig. 1 depicts a block diagram representing the identification process. A discrete time-domain signal $u(k)$, with enough frequency content (*persistent excitation*) to drive the dominant modes to be identified in the system is applied to the system and the output signal $y(k)$ in response to that excitation is measured. The same input sequence is used to drive a discrete mathematical model of the system. This model can be represented by following equation,

$$\begin{aligned} x(k+1) &= f_k(x(k), u(k), \theta) \\ y(k) &= g_k(x(k), u(k), \theta) \end{aligned} \tag{1}$$

where $x(k)$ is the state vector, $y(k)$ is the output sequence signal, and θ a set of model parameters that is adjusted by the identification algorithm to minimize a cost error between the output sequences of the real system and the mathematical model.

Eqn. 1 represents a generic non-linear system, if the system is linear, it can be simplified by the following state space representation,

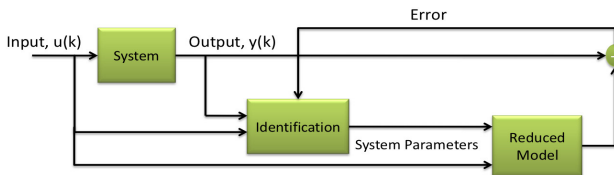$$\begin{aligned} x(k+1) &= Ax(k) + Bu(k) \\ y(k) &= Cx(k) + Du(k) \end{aligned} \tag{2}$$

Figure 1: Block diagram of system identification.

where the constant matrices A, B, C, D contain the parametric information of the dynamic model of the system represented by θ in Eqn. 1.

IDENTIFICATION OF BUNCH DYNAMICS FOR CERN SPS RING

To design and validate the identification algorithms, we are representing the motion along the bunch using macro-particle simulation codes (C-MAD, WARP) [6] [7]. These codes provide a useful tool to represent, via macro-particles, the motion of the particles within the bunch. In the simulation multiple parameters representative of the machine operation can be adjusted. In these codes we introduce realistic models of the frequency response of the amplifiers, cables and kicker used to drive the bunch. Via the simulation the bunch is driven using defined excitation signals and the vertical displacement is computed for different sections of the bunch. Simulated input/output data sets representing the bunch response to defined input signals are valuable to design identification algorithms, address cases involving multiple machine parameter configurations, etc. The identification of the individual bunch dynamics in the SPS ring requires development of wide-bandwidth hardware to drive the individual sections of the bunch and identification algorithms able to capture in a reduced model the dynamics of multi-particles within the bunch. This also explores new beam diagnostic techniques which give us an opportunity to validate nonlinear macro particle simulation codes with real measurements taken from machines.

Simulation Results for Time Varying Parameter Identification

Our initial design of identification algorithms to extract a reduced model of the bunch dynamics is focused on the vertical motion of the bunch when it is driven by an external signal without the presence of e-cloud and TMCI. The nonlinear effects and synchrotron motion of the particles within the bunch requires a nonlinear reduced model to represent the dynamics of the bunch. The simplest model to include this effect is a linear-time-variant model (LTV). This requires time-varying matrices A,B,C in Eqn. 2, as follows,

$$x(k+1) = A(k)x(k) + B(k)u(k)$$
$$y(k) = C(k)u(k) \tag{3}$$

where the matrices $A(k), B(k), C(k)$ are slowly varying along the turns k. Although linear time invariant (LTI)

system identification is well developed, linear time varying (LTV) system identification techniques are still less mature and open research area.

To test our identification algorithm, we generated input/output data using the macro-particle simulation code C-MAD. In this code, the bunch is sectioned in 64 parts and we excited each one of them using band limited random input signals and measure corresponding vertical displacement as output signal. Since we assumed the reduced model is LTV, we modified LTI system identification methods to be able to capture the time dependent dynamic parameters of the system. Based on the set of multi-input/multi-output (MIMO) signals obtained from the simulation code, we developed an identification algorithm based on matrix fraction description (MFD) [9] from available input-output data. Matrices A,B,C belong to the class of observable canonical forms [9]. To be able to capture time variant system parameters, we modified the LTI algorithm such that we are breaking the data in time into small sections, assuming that in each individual time window the parameters are bounded and changing slowly. Therefore, this window technique is used to estimate different sets of parameters corresponding to each of the time windows. These time windows are overlapping in some regions depending on time duration of the interval and the order of the estimated system.

Results from the identification algorithm are depicted in Fig. 2, where the original C-MAD data and estimates from the identification algorithm are compared. The vertical motion of 3 particular slices of the bunch calculated by C-MAD code is depicted by the solid line, while the slice data generated by the reduced model is shown in dotted lines for 300 turns in the SPS machine.
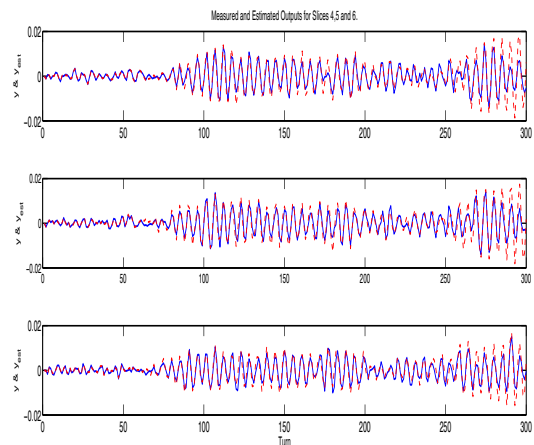

Figure 2: Results of system identification technique to capture time varying parameters, comparing the vertical motion of different bunch slices. *Solid*: Vertical displacement from C-MAD, *dotted*: Vertical displacement estimated by the reduced model

Hardware Development for Excitation System

To allow driving selected bunches at the SPS ring with wide-band arbitrary signals synchronized with the machine cycle, we have developed a system based on a 4 GS/sec. waveform generator. Figure 3 shows a block diagram of the set-up installed at the SPS in July/August 2011. The system uses a synchronized master oscillator to drive data streams at 4 GS/sec. from a local memory. A trigger and synchronization system allows the selection of a single or multiple bunches after synchronization to an injection trigger with respect to a revolution fiducial, and for each turn a unique 16 or 32 sample/bunch excitation is generated and applied to the selected bunch(es) for 15,000 turns of data. These excitation sequences allow driving spectrally shaped noise sequences, or narrowband signals, to excite internal bunch motion. The baseband D/A signal is amplified by 4 100W 20-1000 MHz RF amplifiers, which drive an existing wide-band pickup electrode as a vertical kicker. The vertical motion of the bunch is recorded using 20GS/sec oscilloscope allowing structure within the bunch to be recorded. This system allows the beam excitation using a synchronous deterministic signal concurrent with 20 GS/sec. recordings of the beam motion and excitation waveform. That is the heart of the system identification process to model the bunch dynamics.
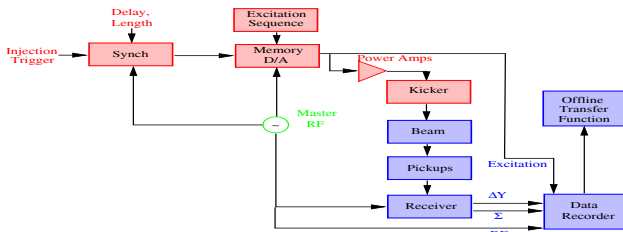
Figure 3: Hardware Configuration for Excitation and Measurements .

We used this hardware setup in our August 2011 MD. The basic goal of the first experiment was to excite different internal modes of the bunch, e.g. mode 0 and mode 1 (head-tail) to test our excitation system. Figure 4 shows vertical dipole motion of 25 super imposed turns. The data clearly shows the *head-tail* excitation. This is a very promising step that shows we can excite the beam even with the existing band-limited kicker structure in the tunnel.

CONCLUSION AND FUTURE WORK

Identification of time dependent bunch dynamics via the reduced model is promising to understand bunch dynamics in the presence of e-cloud and TMCI. It is also coupled with parallel efforts to use nonlinear beam simulation models. This will enable us to validate simulation codes with real machine measurements and to develop useful beam diagnostic methods which use both experimental and theoretical information.
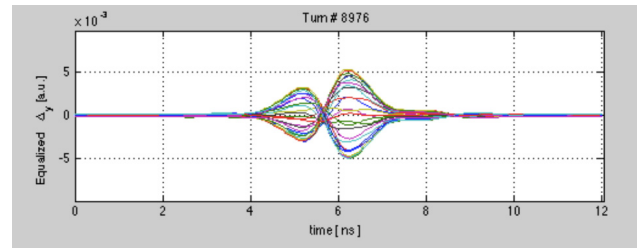
Figure 4: SPS measurement of vertical dipole motion of the bunch for 25 complete superimposed turns showing a head-tail (mode 1) motion.

The immediate next step is to excite the beam with band-limited noise and use this identification process to study internal modes. These experiments and analysis of data will also help us to understand the requirements (such as system bandwidth, noise floor, power level, etc.) of a potential feedback system, and evaluate potential implementation options, such as design parameters of a new wideband kicker structure.

ACKNOWLEDGEMENTS

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