IMPLEMENTATION OF TRANSVERSE DAMPERS IN BEAM STABILITY ANALYSES

Kevin Li and Jani Komppula
CERN, Switzerland

Abstract

Collective effects in high intensity, high energy particle accelerators and colliders are becoming increasingly important as performance is continuously pushed to the limits. The mitigation of collective effects, in particular coherent beam instabilities, relies heavily on transverse feedback systems. The dimensioning of these feedback systems (i.e., power, bandwidth, pickup and kicker distribution) are key to the systems performance and its effectiveness in combating collective effects limitations. Consequently, their realistic modeling in computer simulation codes is also highly important. In this paper we will briefly outline recent developments in advanced modeling of transverse feedback systems in collective effects using the example of macroparticle simulation codes developed at CERN.

INTRODUCTION & MOTIVATION

Collective effects and coherent beam instabilities are important players in today's accelerator landscape as the machine performance is continuously pushed towards the limits of the intensity and the energy frontiers. Collective effects problems are difficult to handle purely analytically (e.g., using 2-particle models or Vlasov solvers). Today's simulation tools derive from different approaches, each with their own advantages and fall-backs. Different type of simulation codes include:

Vlasov solvers: semi-analytic solution of the Vlasov equation in frequency domain using decompositions of the longitudinal phase space in specific basis functions (Laguerre polynomials, Airbags...);

circulant matrix models: matrix model representation of the particle dynamics in a specific basis (decomposition of longitudinal phase space), with linearized collective effects, including transverse feedbacks;

macroparticle trackers: Monte-Carlo-like approach, very close to the physical reality resembling the involved processes in a nearly one-to-one mapping.

Not all of these tools will be covered in this paper. Instead here, due to their universality and flexibility, we will focus exclusively on macroparticle simulation codes; in particular, for this paper we will base ourselves on the example of the PyHEADTAIL collective effects simulation suite [1] which is the simulation code used at CERN for collective effects beam dynamics studies.

As much as it is important to be able to simulate the driving forces of coherent beam instabilities, it is also important to have good models of the mitigation methods. One important example of mitigation devices is transverse feedback systems. These systems themselves carry a high level of complexity. In order to correctly include the effects of transverse feedback systems along with their peculiarities and limitations, it is crucial to ensure a good and complete as possible modeling of the feedback chain. In the following sections we will first stress the importance of feedback systems for collective effects mitigation. We will then show different possibilities of modeling these and then show an example of an implementation of a detailed feedback systems model. Finally, we will present some benchmarks and comparison with experimental data.

TRANSVERSE FEEDBACK SYSTEMS - THE NEED FOR IMPROVED MODELING

Transverse feedback systems are an integral component of any modern particle accelerator. They serve a multitude of purposes ranging from injection oscillation damping, suppression of coherent beam instabilities or as multipurpose tools used for controlled emittance blow-up or tune shift measurements, for example. Essentially, they are a key component for ensuring beam quality preservation throughout the accelerator cycle. Future accelerators will rely heavily on transverse feedback systems, as they are being operated closer to the stability limits. System upgrades be it for increased resolution, more power or higher bandwidth, for example, will become crucial. To correctly characterize and dimension future transverse feedback systems, it is important to include good models in our computer simulation codes.

A simple and pretty straightforward way of modeling of the effects of a transverse feedback system in macroparticle models is by applying a correction on each individual particle proportional to the mean position of the full particle ensemble:

$$x_i = x_i - g \cdot \langle x \rangle \,, \tag{1}$$

where g is the gain defined as the damping rate in turns. In a linear machine with an initial offset x_0, this leads to an exponential decay of

$$x(T) = x_0 \exp\left(-g\,\frac{T}{2}\right) \,, \tag{2}$$

where T is the number of turns. Already this simple modeling can exhibit some interesting effects which have been recently discovered and investigated more closely in different studies [2, 3]. On the other hand, many of the specific features characteristic to realistic feedback systems, such as separation of pickup and kicker, signal delays, imperfections such as noise or bandwidth limitations etc., are not at all captured. A more accurate modeling involves a detailed representation of the actual feedback chain.

Typically, two rather separate approaches are taken when studying feedback systems dimensioning and performance. From the feedback engineer's point of view, the beam dynamics are kept simple and often modeled as an harmonic oscillator. All complexity of the feedback chain, on the other hand, is well captured as highlighted in Fig 1

Contrary to this, the beam dynamics physicist has detailed models of the beam dynamics, including full impedance models and non-linear effects, but treats the feedback system either fully independently or as a simple local correction of the beam orbit (see Fig. 2 for an example of evaluating the feedback performance purely analytically). For a complete modelling of the full system, the two individual subsystems need to be combined while retaining all of their complexity.

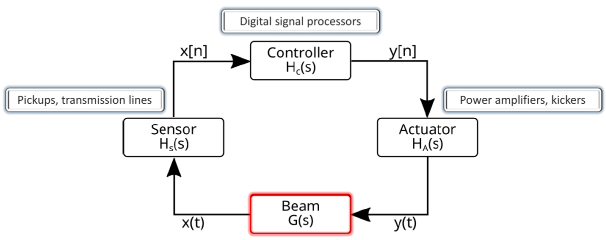


Figure 1: The engineer's view on the internal of a coupled feedback-beam dynamics system. The beam model is kept simple.

To stress the importance of a combined modeling of both feedback loop and collective effects beam dynamics, Figs. 3a and 3b show a study which highlights

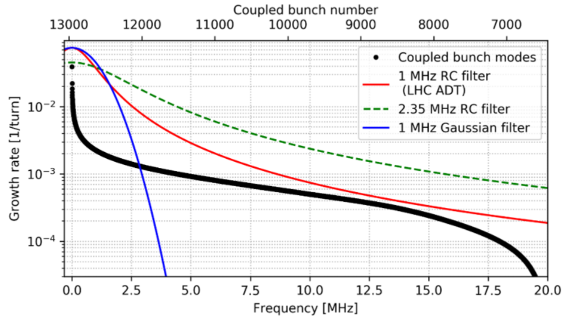


Figure 2: The beam physicist's point of view of a coupled feedback-beam dynamics system. The feedback system is modeled as a simple orbit subtraction at a given point (see Eq. 1).

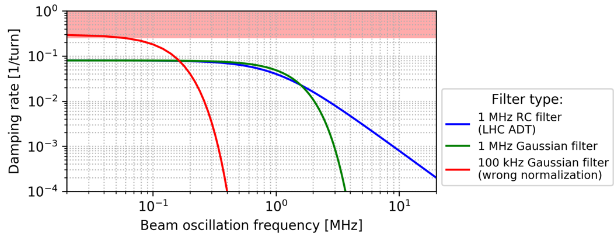
the limitation of realistic feedback systems under tune shifts. For this study, a realistic model of the LHC transverse feedback system (ADT) was implemented and its performance was studied in terms of damping rate of injection oscillations of an injected beam into the machine. It becomes clear, that for instance bandwidth limitations, as highlighted in these figures, can significantly limit the dynamic range of the feedback systems and the gains that can be set. These limitations are not visible using the conventional feedback system models commonly implemented in beam dynamics simulations, as mentioned earlier on.

IMPROVED MODELS IMPLEMENTATION

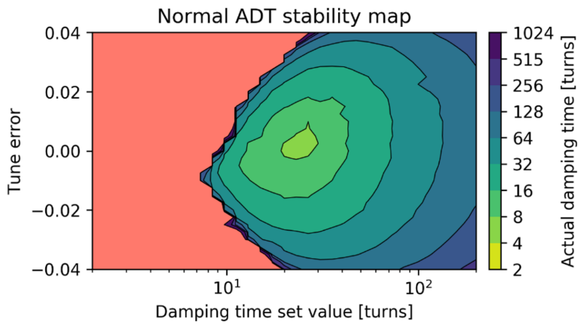
Recently, advanced simulation models have been developed to better represent numerically realistic feedback systems, with much of their specific complexity and details included [4]. The components of these advanced models have been organized in a similar fashion following a similar architecture as the PyHEADTAIL collective effects simulation suite. The latter features:

- a highly modular design;
- very simple and concise individual modules as building blocks;
- a majority of code written in Python with some few methods written in optimized Fortran or C to overcome performance bottlenecks;
- a unique interface for a generic, quick and simple assembly of a wide range of simulation studies.

Following this exact Philosophy, a dedicated feedback module has been prepared, which can be used



(a) Low-pass filters simulate bandwidth limitations the the feedback system and limit the available range of gains; in this case, the bandwidth limitation affects the bunch-to-bunch or intra-bunch oscillation mode that can be resolved and consequently be damped by the system.



(b) The correction kick is computed internally within a digital signal processing chain. Any deviation of the beam from the design tune leads to sub-optimal damping or event to feedback system-driven instabilities.

either independently or in conjunction with PyHEADTAIL.

The applicability of this same approach becomes clear if one highlights the similarities between the two problems, namely signal propagation in a feedback loop and beam dynamics in a synchrotron.

For beams circulating in a synchrotron, one may consider particle ensembles which periodically encounter the same set of machine elements which exerts a certain given action on them. As such, one can concatenate a series of actions which are chronologically and periodically applied to the particle ensemble as the latter circulates within the ring. This very concept is represented, in PyHEADTAIL for instance, by the so-called one-turn-map which essentially is a list of different elements such as betatron maps, synchrotron maps, wake fields, space charge, electron clouds etc.; this list forms the accelerator tracking loop.

If one now thinks about a transverse feedback system, a beam signal gets registered at the pickup and is then propagated though a digital signal processing chain. There, it get transformed over several stages into a correction signal that gets played onto the kicker, which then applies a correction kick back onto the beam. This takes place turn after turn such that one again finds back a sequence of actions that is periodically applied, this time, however, onto the beam signal. In a similar manner as the one-turn-map, a list of signal processors can be constructed, consisting for instance of harmonic ADCs, Notch + Hilbert filters, N-tap FIR filters, upsamplers, DACs, low-pass filters, etc., through which the digital signal is passed turn after turn; this list now forms what can be identified as the feedback loop.

Figures 4a and 4b show an example of such a digital signal processing chain represented as a Python list. One can also see how the digital signal can be inspected at every step within the processing chain. We cannot go into the formal details on the implementation of each elements of these lists, but the idea is that any possible implementation of nearly arbitrary complexity can easily be developed and concatenated to be made available as part of the feedback processing chain.

TESTS AND BENCHMARK RESULTS

The new feedback module was used to investigate phenomena which can not be reproduced using conventional methods to model transverse feedback systems in (macroparticle) simulation codes. On one hand, this serves as an important test and benchmark for the simulation model and, on the other hand, the same model was also used to perform an actual optimization campaign of an exiting transverse feedback system.

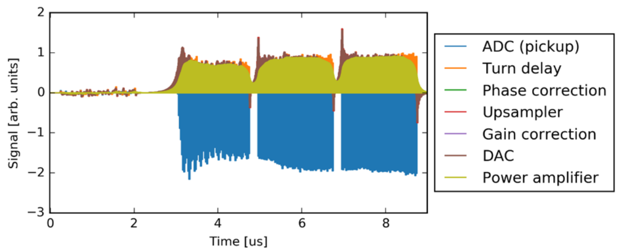
Injection oscillation damping in the LHC

An important function of the LHC transverse damper is the quick suppression of injection oscillations to prevent emittance blow-up after injection. Beams in the LHC are injected in batches of 72 bunches separated by 25 ns. The ADT does not intrinsically have the bandwidth to act on the individual bunches of this spacing (this would require a minimum bandwidth of 20 MHz to be able to act on the highest beam mode). Instead, the damper couples neighboring bunches [1]. One characteristic feature of such a system is the roll-off of the effective gain towards the ends of the injected batches. This can be observed in measurements as an increase in the damping rate at the batch edges. Such a feature can not be reproduced in simulations using the classical approach of modeling feedback systems. A realistic

[1] there are certain high bandwidth settings of the ADT, which can be used to artificially increase the damper bandwidth; this is done by a clever signal processing [5]

```
processors_x = [
        ChargeWeighter(normalization = 'segment_average'),
#         NoiseGenerator(RMS_noise_level),
        HarmonicADC(1*f_RF/10., ADC_bits, ADC_range,
                    n_extras=extra_adc_bins),
        TurnFIRFilter(turn_FIR_filter_x, machine.Q_x, delay=1),
        FIRFilter(FIR_phase_filter, zero_tap = 40),
        Upsampler(3, [0,3,0]),
        FIRFilter(FIR_gain_filter, zero_tap = 32),
        DAC(ADC_bits, ADC_range),
        Lowpass(fc, f_cutoff_2nd=10*fc),
        BackToOriginalBins()
]
```

(a) The feedback loop represented as a digital signal processors list.



(b) The original input signal can be followed and inspected throughout the digital signal processing chain for diagnostics purposes.

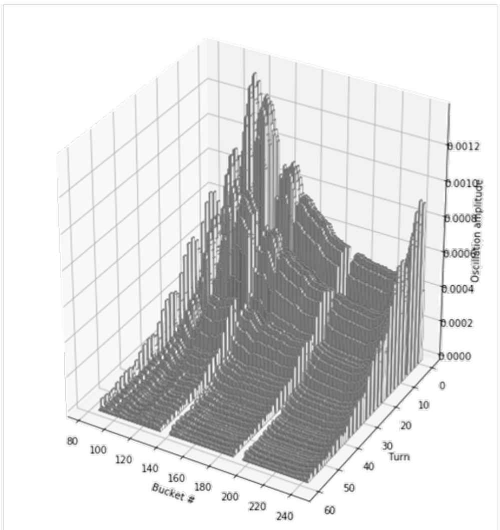
implementation of the ADT should, however, clearly display this feature.

Figure 5a shows a measurement turn-by-turn and bunch-by-bunch of three injected batches into the LHC. The image clearly reveals the aforementioned effects of increased damping rates towards the batch edged. Figure 5b shows the same process modeled in simulations, where a realistic model of the ADT has been implemented using the PyHEADTAIL feedback module. It is apparent, that almost all features of the measurement are well captured by the simulation. This gives confidence that the specific features of the ADT are well modeled in these simulations.

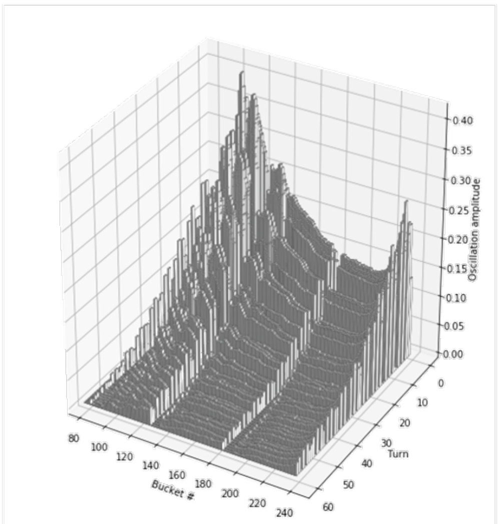
FIR filter optimization for the LHC ADT

Another peculiar feature of transverse feedback systems is the sensitivity of their performance to the design tune. This is impacted by several factors such as delays, lengths of filters, or the present oscillation modes of the beams. In fact, one important design criterion of a transverse feedback system is also its acceptance in deviation from the design tune. This can be an important aspect when taking into account bunch-by-bunch tune shifts from collective effects such as narrow-band resonator impedances or electron clouds, for example.

This time, the realistic numerical model of the ADT was used to design and evaluate in simulations an FIR filter with the target of an increased acceptance in tune deviations – we will call this the tune bandwidth, for now – compared to the FIR filter currently implemented for the ADT. After validation of the improved performance in simulations, the FIR filter was implemented in the firmware of the actual ADT and the experiment was repeated in a machine development study (MD) [6]. Figure 6 shows the results obtained in simulations and in the MD in comparison. It becomes immediately clear, that the numerical model of the ADT very well reproduces the actual feedback system behavior. It is also evident, that by means of the numerical simulation



(a) Turn-by-turn and bunch-by-bunch oscillation amplitudes of the three batches after injection into the LHC as registered by the ADT pickups.



(b) Turn-by-turn and bunch-by-bunch oscillation amplitudes of the three batches after in the injection into the LHC, simulated with a realistic model implementation of the ADT.

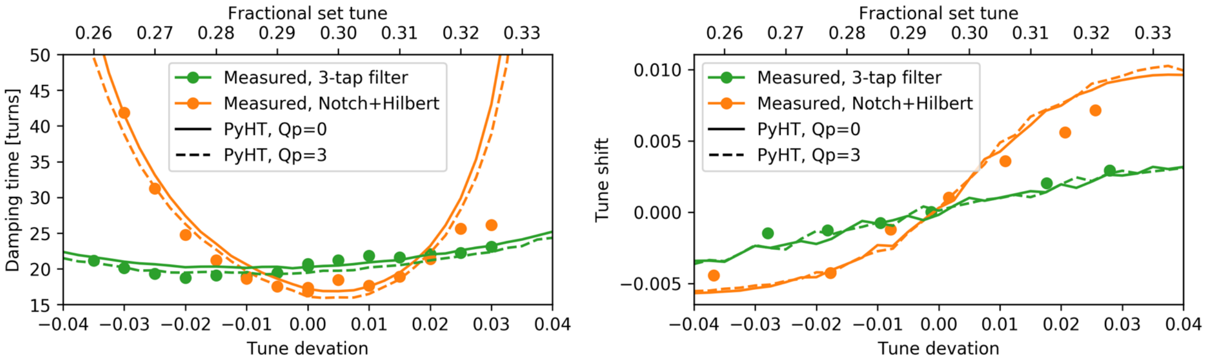


Figure 6: Comparison of simulations and measurements for the design of a high tune acceptance FIR filter in the LHC.

it was indeed possible to produce an FIR filter which features an improved performance in term of tune bandwidth. This is a very important achievement as it shows that with good and detailed numerical models of transverse feedback systems, it is actually possible to make meaningful studies the help support the design and dimensioning of both existing as well as future feedback systems. It can also save valuable machine time which would be needed to do the same types of studies in MDs.

SUMMARY AND CONCLUSION

In this paper we highlighted the importance of accurate and realistic modeling of transverse feedback systems in simulations. Collective effects limitations are becoming increasingly important as future machines are operated closer to the performance limits. With transverse feedback systems as one of the key mitigation devices, their full accessibility through numerical simulations is of utmost importance, to catch limitations and imperfections and allow for accurate feedback dimensioning and design.

We have shown that, recently, a fully featured feedback system module has been developed for the PyHEADTAIL collective effects simulation suite in a highly generic and modular fashion.

The feedback module has been checked against real world measurements done at the LHC with the LHC transverse feedback system (ADT). These benchmarks revealed that many of the peculiarities of the real world system were well captured in the simulation model. Bandwidth limitations manifested in the simulation results as well as the improvements, which were implemented within the digital signal processing change via firmware changes. The latter study also showed how feedback simulations can be used to investigate and improve the performance with offline system optimization for existing machines (i.e. LHC ADT) or advanced system design for future machines (i.e., Future Circular Collider).

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