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CHARACTERISATION OF CLOSED ORBIT FEEDBACK SYSTEMS

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Abstract

Closed orbit feedback is applied at nearly all synchrotrons. Detailed investigations continue to be performed on the mathematical modelling of the spatial part (i.e. related to Orbit Response Matrix) and the dynamic part (i.e. the controller). This talk will serve as a summary of the ARIES workshop on Next Generation Beam Position Acquisition and Feedback Systems in November 2018. Benefits of recent advances compared to the traditional implementations will be highlighted.

INTRODUCTION

Closed orbit feedback (COFB) systems have been installed in most synchrotrons, both light sources and hadron accelerators. This contribution aspires to take a brief view at closed orbit feedback system from the perspective of *control theory*, which is useful as an integral part in the modern synchrotron design process. Furthermore, it will try to highlight some of the recent approaches to the spatial and dynamic processes used in closed orbit feedback with examples from the ARIES workshop "Next Generation Beam Position Acquisition and Feedback Systems" organised and held at ALBA in November 2018 [1]. While COFB has a long legacy in synchrotrons, digital real-time feedback systems operating at rates of 10 kHz and above have become widespread, so particular aspects affecting their performance will be focused on. It should be noted that most theoretical aspects are excellently covered in PhD thesis [2, 3], so this paper can only serve to give a brief introduction.

Motivation for Closed Orbit Feedback

Synchrotrons store relativistic charged particle beams for various reasons: the origins lie in high energy physics and storage rings for rare species, but also synchrotron light sources have become a widespread scientific tool globally. Whichever the motivation for the operation of a synchrotron ring, there will frequently be a desire to control the closed orbit of the particle beam, since disturbances of the magnetic guide fields are hard to limit to the degree that would allow operation without feedback control.

In practice, a specification on the standard deviation of orbit is set and this is frequently expressed as a an absolute distance or a fraction of beam size (or angle) in a relevant location. In light sources, this will provide an electron beam that is not significantly deteriorated by orbit motion so that photon beams are produced stably. In a particle collider it might help to ensure a constant collision rate, while in a ramping synchrotron it will be required to enable predictable extraction trajectories independent of hysteresis or other disturbances. This orbit stability deviation needs to be accompanied by a frequency or time duration range over which the specified deviation should be integrated. This range will lead to further considerations on the requirements for beam position monitors (BPMs), like electronic noise, impact of thermal expansion or ground motion of the support.

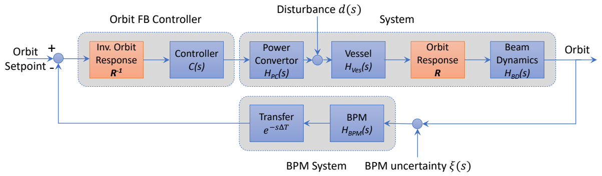

Figure 1: Block diagram of a simplified closed orbit feedback system: blue blocks signify dynamic processes, while red blocks show spatial processes.

CONTROL THEORY

COFB is an excellent fit with the common definition of a control loop in the context of control theory. Readers unfamiliar with terms like disturbance rejection, unity gain crossover frequency, open loop gain etc. can find an introduction in this tutorial aimed specifically at physicists [4]. For the purposes of COFB, the sources of orbit distortions in synchrotrons are well enough described by the following equation [5]:

$$\Delta x = \Delta x' R_{ij} = \Delta x' \frac{\sqrt{\beta_i \beta_j}}{2 \sin \pi \nu} \cos\left(|\Psi_i - \Psi_j| - \pi \nu\right)$$

In each transverse plane a kick $\Delta x'$ creates an orbit Δx and $\beta_{i,j}$, $\Psi_{i,j}$ are the respective beta function and phase advance at the location of the kick and observation. The presence of the betatron fractional tune ν in the denominator acts a a reminder to minimise orbit distortions during magnetic lattice design, by keeping ν near 0.5. The Orbit Response Matrix (ORM) is assembled from the elements R_{ij} by iterating through all the locations of dipole disturbances and observables. For use in COFB this is limited to corrector magnets and BPM locations.

Dynamic and Spatial Processes

Figure 1 attempts to map the generic feedback structure of controller, system, monitor to the typical implementation in the case of COFB. Inside this block diagram dynamic and spatial processes are identified:

- Dynamic processes: these are systems with the ability to store energy or information and thus display a dynamic response to the input on the output. If we limit

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our considerations to **linear time-invariant** systems, then the time domain behaviour is described by the impulse response $h(t)$ and the frequency domain by the transfer function $H(s) = \mathscr{L}\{h(t)\}$. Power converters, magnets and vessels, as well as filtering in the BPM and computation/transport delays are best expressed this way to state their behaviour in the loop.

- Spatial processes: these translate between a number of input and output values, for COFB this is typically the ORM and its (pseudo-)inverse. Their time domain behaviour is instantaneous, the frequency response is flat.

The dynamics of the whole COFB loop is trivial to estimate if it can be assumed that all BPMs and all correctors have identical dynamics. Typical assessments produce a sensitivity, for instance disturbance $d(s)$ to orbit $y(s)$ and display this as a Bode plot, i.e. magnitude and phase over frequency. However, it is essential to have knowledge of all the components in the loop to get a realistic estimate. Particular care is advised not to overlook potential sources of latency.

Origins of Latency

There can be various causes for latencies or delays which are found in COFB.

- Systematic: Low pass filters in BPMs are unavoidable in the process of decimation. Signals need to be filtered before decimation to avoid an additional noise contribution from above the Nyquist frequency, but this will create group delay or latency. The group delay can be calculated from the knowledge of the filter coefficients. As a rule of thumb, a filter with a sharper drop will create a longer latency. As a consequence, the only way to reduce this latency is to increase the sample rate of the whole feedback loop.

- Physical: The transport of data through long cables or fibres to collect and distribute the orbit and corrector settings creates an unavoidable latency [6], though this remains still a small contribution is most cases today [7]. More importantly, eddy currents in magnets and vacuum vessels produce both low pass filter behaviour and latency. The component from vessels can be analytically computed or measured [8, 9].

- Programmatic: As signals change into digital representations, delays are a trivial accident. For instance, latency jitter is introduced by uncertainty in the time till an interrupt routine is served in an operating systems [10, 11]. At the same point, different measurements (benchmark tools) are required to pin down and optimise delays. In practice, good results have been achieved for COFB controller implementations with field programmable gate arrays (FPGA) [7], digital signal processors (DSP) [12, 13] and central processing units (CPU) [14, 15] alike when care has been taken.

  On the other side, areas like power converters with built-in digital control loops are easy to overlook.

Whichever the cause, the effect will always be to the detriment of performance of the COFB. With increasing latency, the crossover frequency of the closed loop transfer function will be lowered, and suppression will be reduced at all frequencies below crossover. While some latencies can be analytically calculated, they should be complemented by measurements. This can be done using the same process that will give information about a the frequency response.

SYSTEM IDENTIFICATION

System identification is a method that can be applied to many components or even the whole COFB. The principle is based on providing a known input signal to a system with unknown dynamics (device under test or DUT) while recording both input and output signals. If linear time-invariance can be assumed of the DUT, then the transfer function can be calculated from knowledge of the output and input signal. In most cases it is sufficient to fit the transfer function with a simple model, for instance a first order low pass filter with added latency:

$$G(s) = K\frac{e^{-st}}{\tau s + 1}$$

In this equation, K is the pass band gain of the low pass filter, $\tau = 1/\omega_C$ is the filter time constant (inverse of cut off frequency ω_c) and t is the latency which adds further linear phase shift without any modification of the amplitude response.

The idea of system identification can be applied to all components or assemblies of components in the loop, some examples are given in Table 1. It can be applied in simulations and measurements alike, but system identification across the analogue/digital boundary is reliant on prior knowledge of latency of analogue/digital converters.

There are three types of excitation signals used widely in system identification:

- Sweeps: a sinusoidal signal changing in frequency over time. This is used in instruments like swept lock-in amplifiers, vector network analysers or frequency response analysers, which can be found as options in modern oscilloscopes. In COFB this has been used to identify the characteristics of magnets and vessels [9].

- Impulse or step response: The precise timing of the impulse or step needs to be recorded to allow complete

Table 1: Examples of System Identification

Input	**System**	**Output**
Current	Magnet	B field
Beam position	BPM system	Orbit reading
Input data	Control Process	Output data
Setpoint	COFB loop	Measurement

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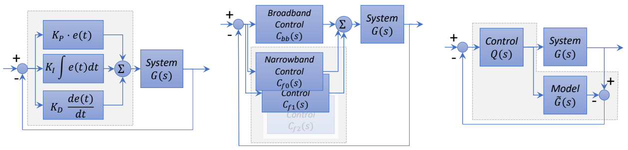

Figure 2: Some frequently used control algorithms in COFB. Left: Proportional-Integral-Derivative, middle: Broadband control with harmonic suppressors, right: Integral Model Control

measurement including latency. In practice there will can be challenges from signal to noise or the precise properties of the impulse. Step response measurements are the standard in many control loop applications [4].

- Cross-correlation: In general, also a (pseudo) noise signal can be used as input. As long as both input and output are recorded the impulse response can be retrieved by cross-correlation [16].

Using this technique early on in the design of COFB will improve the quality of predictions and ultimate performance of the closed loop behaviour. However, the choice of control algorithm is of equal importance.

CONTROL ALGORITHMS

Various different algorithms have been employed for the digital controller in COFB, some of the more commonly used are shown in Fig. 2. The Proportional-Integral-Derivative controller (PID) stems from a time when controllers were built with analogue electronics, but the concept has been translated into the digital age. The advantages of PID are the intuitive understanding and some documented empirical tuning approaches [17, 18], but it is somewhat ill suited to the significant latency often found in COFB. In this case the D-term is often disabled, and the P and I reduced, leaving a operating but sub-optimal system.

To compensate for lower crossover frequency, narrow band filters with adjustable gain and phase can be added in parallel to the broadband control algorithm. These have found good use in suppressing the harmonics of mains as often found in beam position spectra [10, 19].

An approach better adapted to the presence of latency is a Smith compensator [2] or the more generalised concept of Internal Model Control (IMC) [14, 20]. Both these techniques require a knowledge of the system under control. In turn, they calculate the input to the controller from a difference between the system and a model of the system including the effects of latency, thus avoiding a oscillatory tendency otherwise observed when loops are closed. It should be noted that in practice the implemented digital controller will be a higher order infinite impulse response filter, and IMC is merely used to calculate the filter coefficients of this.

ORM Inversion Strategies

Early automated orbit correction was optimised to produce maximum effect with a minimum number of magnet variations. This reduced both computations and actual physical movements of quadrupoles which were the adjustments of the time [21]. Such limitations are neither necessary nor useful in the days of multitudes of remote controlled corrector magnets, so Singular Value Decomposition (SVD) and the related Truncated SVD (TSVD) technique advanced to success in the late 1990s [12].

However, these two leave potential for a new issue: if the inversion of the ORM is ill-conditioned (the ratio of largest to smallest singular value is large, maybe >1000) a full SVD or TSVD with the same number of singular values as corrector magnets will produce a result that is ill suited for feedback application as it emphasises the uncorrelated noise of monitors. One option is to reduce the number of singular values in TSVD further, but this results in a distributed static orbit error and leads to coupling of individual monitors, thus limiting beam steering with a individual BPM offsets.

Tikhonov Regularisation

Tikhonov regularisation offers an alternative technique to control the impact of the weak singular values during inversion. Originally introduced to accelerator physics at NSLS [22] in the context of orbit correction it was later implemented in faster COFB schemes [14, 19]. It offers itself also for later introduction into already implemented COFB, as it requires only a small variation in the production of the pseudo-inverted ORM. The Tikhonov regularisation applied to matrix inversion of $R = U\Sigma V^*$ uses

$$D_{nn} = \frac{\sigma_{nn}}{\sigma_{nn}^2 + \alpha^2} \tag{1}$$

to compute the regularised inverse ORM $\hat{R} = VDU^*$. The regularisation parameter α reduces the impact of weak modes in the inversion process, but since the same regularised inverse ORM is re-applied frequently, these weak modes are still ultimately driven to zero. In the feedback context, the regularisation can be perceived as a lower gain for weaker modes, leading to slower settling time and lower sensitivity crossover frequency just for these modes. This is an acceptable compromise, since these modes carry little power, so their reduction is not the highest priority.

Rather than limiting the regularisation to a single parameter, the concept can be extended with the introduction of mode-by-mode control. This idea uses individual gains or sets of parameters for each mode. First realised in the 2000s [23] this feature is now available in commercial FPGA implementation [7] and in use at for instance at Taiwan Photon Source [24]. However, the addition of new parameters requires further optimisation to adapt the feedback system to the particular noise spectrum of spatial and frequency nature [25].

Table 2: Performance parameters of a subset of COFB systems presented at the joint ARIES workshop. Values in brackets denote aspirations for future systems

Machine	Latency [µs]	Corrector BW [Hz]	Sensitivity crossover [Hz]
LHC [6]	>10,000	1	0.5
EBS [26]	630	500	(150)
Astrid-2 [15]	600-800	1,000	150
Petra-III [27]	338	1,000	150-200
AS [10]	120	1,000	300
SIRIUS [8]	(20)	10,000	(1,000)

ARIES WORKSHOP

The joint ARIES workshop on Electron and Hadron Synchrotrons focused on ”Next Generation Beam Position Acquisition and Feedback Systems”. During the workshop’s three day programme, nearly one complete day was spent on COFB systems, with reports from established facilities and plans for upcoming new systems. Some of the talks concentrated on plans for new BPM systems, so only a subset of talks will be referred to here.

Besides the question about controller algorithms and their features, technological implementation details were a major theme:

- Procurement: Should the controller hardware, software and firmware be built in house or should it be sourced commercially?
- Hardware: Should the controller hardware be based on FPGA, DSP or CPU?
- Upgrades: In case of an upgrade, should the complete system be replaced or should working parts be carried over?
- Interfaces: Which technology should be chosen for the inputs and outputs of the controller?

Unsurprisingly, no unique answers to these questions emerged, as these are mainly moderated by the individual conditions at the relevant accelerator.

An overview of the COFB performance parameters of some selected synchrotrons is given in Table 2. It illustrates the aforementioned connection between latency, corrector bandwidth and sensitivity crossover frequency: As latency shrinks and corrector bandwidths increase in modern implementations, the achieved sensitivity crossover frequency rises.

Established Synchrotron Light Sources

A cost effective solution for a small light source with only 24 BPMs and 12 corrector magnets was presented in the talk about COFB at ASTRID-2 [15]. It utilised a combination of commercial BPMs (which already existed) and in house built digital to analogue converters (DAC) to send updated fast adjustments to the existing analogue corrector power supplies. The feedback controller was realised using LabView RT® on a standard personal computer equipped with a commercial FPGA card to enable communication with the DACs.

The Australian Synchrotron had made attempts using a CPU based approach initially as well, but found that reducing the jitter in the RT Linux proved difficult [10]. Nevertheless, this approach provided a good test bed for prototyping COFB, which was ultimately implemented on FPGA. In the ultimate implementation, this led to a well performing system including PI controller and harmonic suppressors. The system also uses a mixture of slow and fast correctors using the approach previously implemented at Soleil [28] and Tikhonov regularisation [19].

At PETRA-III a large system with 250 BPMs and 100 fast correctors is driven with data at turn-by-turn rate of 130.1 kHz, which makes this the COFB system with the highest data processing rate currently in operation [27]. Combining commercial BPMs with in house FPGA based processing, a PID controller including 50 Hz suppressor was realised. Furthermore, a feed-forward system adds a fast correction signal to the repetitive error that occurs as a result of every top-up injection.

New and Upgraded Synchrotron Light Sources

The ESRF is currently in the process of upgrading to the new storage ring labelled Extremely Bright Source (EBS). The COFB system had been upgraded a few years ago, it will only be augmented with additional BPMs and correctors during the current storage ring upgrade. In the end, the system will operate with 192 fast and 128 slow correctors together with 96 fast and 192 slow correctors. There will be two interlinked systems of fast and slow control to maintain the COFB performance at the same level as before the storage ring upgrade [26]. The system will also continue to operate with PID, 50 Hz suppressor and feed-forward correction of injection disturbances.

In contrast, SIRIUS is a completely new ring built by LNLS in Brazil [8]. Some fundamental decisions towards high performance COFB have been taken in the past, for instance the thin stainless steel chambers under correctors will allow fields of frequencies up to 10 kHz to penetrate. Complemented by an in house developed BPM hardware/firmware system [29] and FPGA based controller, minimisation of latency was paramount in many design aspects. The aspirations are for the highest performing COFB system to date and advanced control concepts are envisaged as well.

Hadron Synchrotrons

The LHC illustrated the impact of size in terms of ring circumference and technology in terms of slow superconducting correctors [6]. As a result, the performance of automated COFB at LHC is orders of magnitude less when expressed in sensitivity crossover frequency. But similar disturbances from ground vibrations (even from micro-earthquakes) excite orbit changes in the few 10s of Hz, and raise desires to suppress these with a more agile COFB in the future.

A project currently in the installation phase is FAIR in Germany, where a complex of synchrotrons will be used to accelerate and store heavy ion beams. In this context the energy ramping speed can be quite demanding, and a variety of different operating modes will be quickly switched between in sequence [30]. This forms a unique challenge to COFB as an agile system is required to correct errors introduced by hysteresis during energy ramps lasting between 300 ms and 3 s. Furthermore, the ORM is expected to change during acceleration, thus leading to the challenge of deviation of the inverse ORM inside the controller from the actual ORM in the ring.

The impact and limits of this discrepancy have been investigated in theory and comparisons with measurements showed good agreements. Furthermore, matrix inversion using a variety of harmonic analysis for cases of highly symmetric magnetic lattices has been explored [31]. The innovative approach is computationally less intense than SVD, so will be useful where matrix inversion is required while COFB is running.

The implementation is planned using commercial BPMs and commercial FPGA based controller [7]. There might still be variations to the currently existing functionality inside the FPGA, but it is assumed these are compatible with the existing hardware.

CONCLUSION

In summary, the ARIES workshop provided a useful forum for comparison of existing COFB systems and its main components. The multitude of solutions to similar demands was inspiring and helped to abstract the essential criteria for optimisation of performance in the future. In the near term, the COFB performance of upgraded and freshly built light sources will be highly anticipated. But it is remarkable to note that also hadron accelerators have discovered an interest in real-time COFB, and it can be expected this thirst will only expand in the future. In that respect it was most useful that the workshop brought together the people from both light source and hadron accelerator communities.

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