NORMAL MODE BPM CALIBRATION FOR ULTRALOW EMITTANCE TUNING IN LEPTON STORAGE RINGS *

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Abstract

BPMs capable of high-resolution turn-by-turn measurements offer the possibility of new techniques for tuning for ultra-low beam emittance. In this paper, we describe how signals collected from individual buttons during resonant beam excitation can be used to calibrate BPMs to read the beam position in a normal mode co-ordinate system. This allows for rapid minimisation of the mode II emittance, simply by correcting the mode II dispersion. Simulations indicate that the technique is effective and robust, and has the benefit of being insensitive to BPM gain and alignment errors that can limit the effectiveness of other techniques. We report the results of some initial experimental tests of the technique.

INTRODUCTION

Work to achieve ultralow vertical emittances in electron (and positron) storage rings is motivated by the need to improve the performance of light sources and colliders. In recent years, vertical emittances of a few picometres have been reported at a number of storage rings [1–4]. A variety of techniques have been used to achieve emittances in this regime: one common technique, for example, is to use analysis of the orbit response matrix (ORM) [5] to identify and correct the sources of error leading to generation of the vertical emittance. ORM analysis includes the possibility to identify diagnostics errors, such as tilts of the beam position monitors (BPMs) that can limit the correction of coupling errors in some situations. However, data collection for ORM analysis can be slow, and the numerical processing requires the manipulation of extremely large matrices. For large rings, it may become impractical to perform ORM analysis on a routine basis to achieve and maintain extremely small vertical emittances.

In this paper, we outline a technique for low-emittance tuning based on excitation of the normal modes of beam oscillation [6]. Collection of turn-by-turn data during such excitation allows for calibration of the BPMs to return directly the beam position in a normal mode co-ordinate system. This allows in turn direct measurements of the normal mode dispersion: minimisation of the mode II dispersion corrects simultaneously the dispersion and coupling effects

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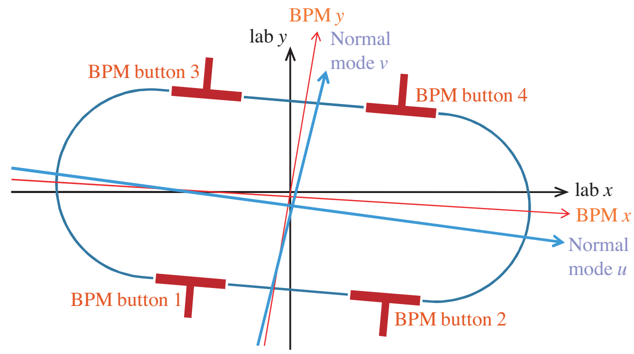

Figure 1: Co-ordinate systems in a BPM. Ideally, all the co-ordinate systems coincide, but alignment, calibration and coupling errors lead to differences between the laboratory, BPM, and normal mode co-ordinate systems.

that generate mode II emittance. Since the BPMs are calibrated directly from the beam motion, the technique is insensitive to BPM gain and alignment errors. Furthermore, data collection is fast and (with the appropriate hardware) straightforward, and the technique can be applied as easily to a large ring as to a small ring.

THEORY

Consider a BPM with four button-type electrodes in a vacuum chamber (see Fig. 1). We can immediately define two distinct co-ordinate systems: first, the laboratory co-ordinates, usually specified (in a planar storage ring) so that the transverse axes are exactly horizontal and vertical; and second, the co-ordinates returned by the BPM as a bunch passes between the buttons. Ideally, the BPM co-ordinates will coincide with the laboratory co-ordinates. However, because of alignment and gain errors, there are always some differences between them. In addition to these two co-ordinate systems, we can define a third system, in which the axes are given by the planes of oscillation of the beam when excited in one or other of the transverse normal modes.

While it is, in general, difficult to calibrate a BPM so that the BPM co-ordinate axes line up with the laboratory co-ordinate axes, calibration of a BPM to read the co-ordinates along the normal mode axes is relatively straightforward, given the appropriate data collected from turn-by-turn observation of the beam while exciting motion in first one, and then the other normal mode. Suppose the beam changes position by Δu along the first normal mode axis, and by Δv along the second normal mode axis. Assuming a linear response, appropriate for small position changes,the button signals change by:

$$\begin{pmatrix} \Delta b_1 \\ \Delta b_2 \\ \Delta b_3 \\ \Delta b_4 \end{pmatrix} = BC \begin{pmatrix} \Delta u \\ \Delta v \end{pmatrix}, \qquad (1)$$

where:

$$B = \begin{pmatrix} 1 & 1 \\ \left(\frac{\partial b_2}{\partial b_1}\right)_v & \left(\frac{\partial b_2}{\partial b_1}\right)_u \\ \left(\frac{\partial b_3}{\partial b_1}\right)_v & \left(\frac{\partial b_3}{\partial b_1}\right)_u \\ \left(\frac{\partial b_4}{\partial b_1}\right)_v & \left(\frac{\partial b_4}{\partial b_1}\right)_u \end{pmatrix}, \qquad (2)$$

and:

$$C = \begin{pmatrix} \left(\frac{\partial b_1}{\partial u}\right)_v & 0 \\ 0 & \left(\frac{\partial b_1}{\partial v}\right)_u \end{pmatrix}. \qquad (3)$$

The matrix C essentially sets the scales of the axes, and can be estimated using a model of the BPM button geometry and signal processing electronics assuming that the normal mode axes are not too far different from the Cartesian axes. The matrix B contains the significant information for constructing the beam motion along each of the normal mode axes, from measured changes in the signals on the four buttons. The components of B can be measured by observing the variation in button signals, while exciting the beam in one or other of the normal modes. For example, if the signals on buttons 1 and 2 are recorded over a number of turns while exciting the beam in normal mode I (in which the position along the v axis is fixed), then a correlation plot of b_2 versus b_1 will be fitted by a straight line with gradient $(\partial b_2/\partial b_1)_v$. Once the calibration matrices B and C have been obtained, then the inverse matrices can be applied to any set of measured changes in BPM button signals, to determine the corresponding change in beam position along the normal mode axes.

As already mentioned, the matrix C essentially sets the scale along each of the normal mode axes. If the goal is to zero the change in beam position along one normal mode axis with respect to some specified change in machine conditions (as in, for example, a change in energy made during a dispersion measurement), then errors in C should not be important. Since the calibration (measurement of B) can be performed quite quickly, it is reasonable to re-calibrate the BPMs after any significant change in beam position.

Suppose that the storage ring is tuned so that a change in beam energy (resulting, for example, from a change in RF frequency) results in motion purely along the mode I axis at a particular location. In that case, the mode II dispersion is zero at that location. Then, any emission of synchrotron radiation at that location will result in excitation of mode I motion only. If the mode II dispersion is zero at all locations where synchrotron radiation is generated, then the mode II emittance will damp to the limit given by the opening angle of the radiation. Hence, to tune a storage ring for minimum mode II emittance, one can perform the following two steps: (1) calibrate the BPMs to read the beam motion along the normal mode axes; (2) tune the machine (using skew quadrupoles, or other convenient correctors) to minimise the mode II dispersion. By eliminating mode II dispersion, mode II emittance vanishes, regardless of transverse coupling. Hence, following the calibration, low-emittance tuning is achieved in a single step. This is in contrast to conventional methods, which often involve separate correction of the vertical dispersion and the betatron coupling.

SIMULATIONS

The BPM calibration and low-emittance tuning procedure outlined in the previous section is easily investigated in simulation. We used a model of CesrTA [7], including a model for the nonlinear response of the BPM button signals to changes in beam position. In the simulation, we first applied a set of alignment errors to the magnets (including vertical alignment and tilt errors on the dipoles, quadrupoles, and sextupoles), and alignment and gain errors to the BPMs. An orbit correction using the vertical steering magnets was then performed. Then, the BPM calibration process was simulated by tracking the beam over multiple turns first in one, and then in the other transverse normal mode. The calibration matrices found from the tracking were applied to determine the mode II dispersion, which was corrected using skew quadrupole magnets, with strengths determined from the nominal response matrix between the mode II dispersion and the skew quadrupoles. The calibration and mode II dispersion process was iterated, and the final mode II emittance calculated. The entire simulation was repeated for 1000 seeds of machine error. Fig. 2 compares the resulting distribution of the emittance for different levels of BPM gain error, in the case that the correction is based on either the vertical dispersion (Fig. 2 top), or the mode II dispersion (Fig. 2 bottom). When using the vertical dispersion, the distribution peaks at just under 50 pm vertical emittance with zero BPM gain errors, and even quite small gain errors can have a strong adverse effect on the final emittance achieved. However, when using the normal mode dispersion, the distribution peaks at less than 10 pm, and is completely insensitive to BPM gain errors.

EXPERIMENTAL RESULTS

Experimental tests of the BPM calibration and low-emittance tuning technique were carried out at CesrTA. The diagnostics system allows for collection of 1024 turns of data from each BPM button, while resonantly exciting the beam in either of the transverse normal modes (i.e. at either of the betatron frequencies).

Fig. 3 shows an example of calibration data collected from a single BPM, during resonant excitation of normal mode I. If the amplitude of the beam oscillation is too large, then nonlinear effects may begin to appear; however,

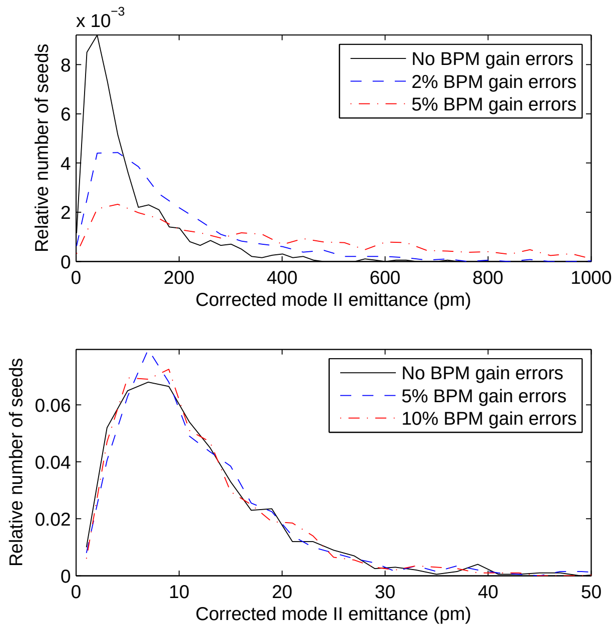

Figure 2: Simulations of emittance correction in CesrTA. Top: distribution of final mode II emittance after orbit and vertical dispersion correction. Bottom: as the top plot, but with correction based on mode II dispersion, rather than vertical dispersion. 1000 seeds of machine error are simulated.

it is possible to achieve amplitudes large compared to the BPM resolution (resulting in a very small scatter of the data points) without the appearance of any nonlinearities.

The normal mode calibration can be tested in a number of ways, including observation of the Fourier spectra, and measurement of the response of the mode II dispersion to changes in disperison and coupling induced by varying skew quadrupoles. The results of these tests are encouraging; for example, using the nominal calibration, peaks corresponding to mode I motion are generally present in spectra of the vertical co-ordinate, as well as the horizontal co-ordinate. However, spectra of the normal mode co-ordinates generally contain only single peaks, corresponding to the appropriate betatron frequency. The results of such tests are reported in more detail in [6].

Initial tests of low-emittance tuning in CesrTA using normal mode BPM calibration also appear promising. In one test, an initial tuning of the machine based on correction of the orbit, vertical dispersion, and coupling, resulted in a vertical emittance of 14 pm (estimated using an x-ray beam size monitor). After turning off the skew quadrupoles, the emittance increased to 24 pm. Then, applying a single correction of the mode II dispersion (after calibrating the BPMs using normal mode motion), the emittance of 14 pm was restored. On that occasion, however, further correction appeared to be limited by the ability to fit the measured mode II dispersion by adjusting the skew quadrupole strengths, and attempts to improve the correction (based on a relatively poor fit to the dispersion) even led to some

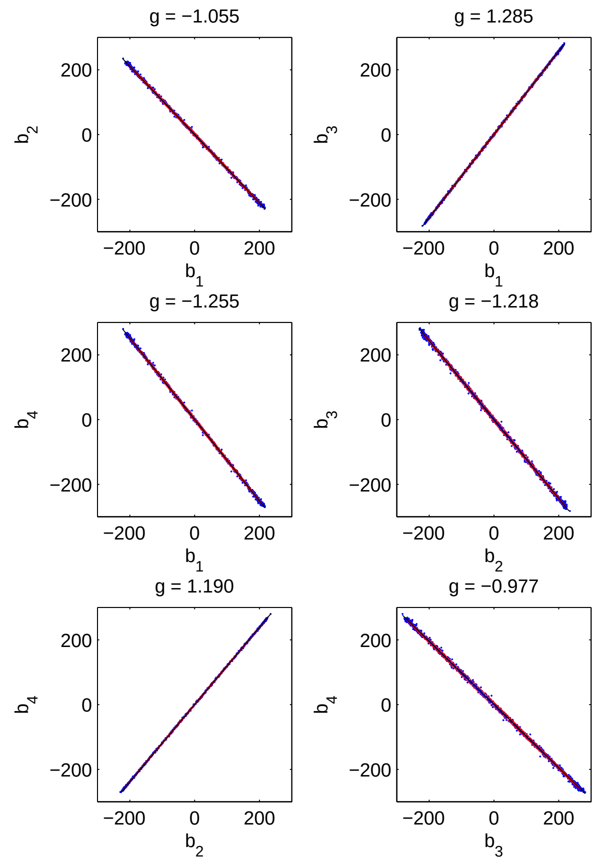

Figure 3: Calibration data from one BPM at CesrTA. Each plot shows the correlation between button signals for 1024 turns of an electron bunch, during resonant excitation in normal mode I. The blue points show the data; the red lines show ellipses fitted to the data. The gradient of the major axis of the ellipse (given as the value g above each plot) gives a component of the calibration matrix B.

degradation of the emittance. It is hoped to carry out further studies to optimize the application of the technique and to understand better the practical limits.

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