A Method of Beam-based Calibration for Beam Position Monitor

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Abstract

A method of beam-based calibration for beam position monitor is proposed instead of mapping by use of an antenna or a wire. The proposed method was applied to the beam position monitors of SPring-8 storage ring.

§1 Introduction

A typical beam position monitor (BPM) consists of four button electrodes. The map function of such BPM is usually measured by use of an antenna or a wire without beam. The map obtained without beam is generally different from the map by the beam passing, because a coaxial wave guide is formed by an antenna or a wire. The TEM mode is the most dominant wave guide mode excited by beam passing. The electric field distribution of the TEM mode excited by an antenna with finite diameter is different from that by beam which is like line charge. Therefore the map measured by an antenna has to be corrected. The correction will be more complicated if higher order modes are excited. The electric field distributions of the higher order modes in the coaxial wave guide with an antenna or a wire are essentially different from that in the ordinary wave guide. For example, in case of SPring-8 storage ring, the BPMs are mounted on the vacuum chamber whose cross-section is complex with ante-chamber, and the beam signal is detected at the rf frequency of 508MHz which is higher than the cutoff frequency (about 350MHz) of the lowest higher order mode TE_{10}. It will be difficult to perform the correction for the maps. To evade the difficulty, a method of beam-based calibration for the BPM is proposed. In section 2, a method of the calibration with beam is described. In section 3, the method is applied to the BPMs of SPring-8 storage ring.

§2 A method of beam-based calibration

As shown in Fig. 1, a beam position monitor generally consists of four button electrodes. The following values $\alpha(x,y)$, $\beta(x,y)$, $\gamma(x,y)$, $\delta(x,y)$ are defined by the output voltages $V1(x,y)$, $V2(x,y)$, $V3(x,y)$, $V4(x,y)$ from each electrode,

$$\alpha(x,y)=\frac{V1(x,y)-V2(x,y)}{V1(x,y)+V2(x,y)} \qquad \text{(eq. 1)}$$

$$\beta(x,y)=\frac{V4(x,y)-V3(x,y)}{V4(x,y)+V3(x,y)} \qquad \text{(eq. 2)}$$

$$\gamma(x,y)=\frac{V1(x,y)-V4(x,y)}{V1(x,y)+V4(x,y)} \qquad \text{(eq. 3)}$$

$$\delta(x,y)=\frac{V2(x,y)-V3(x,y)}{V2(x,y)+V3(x,y)}. \qquad \text{(eq. 4)}$$

Parameters α and β are sensitive to the horizontal deviation of beam. Parameters γ and δ are sensitive to the vertical deviation of beam.

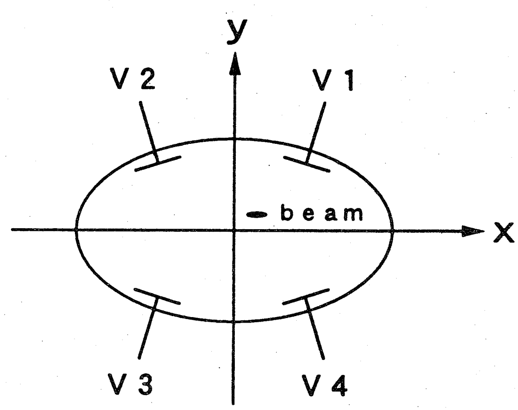

Figure 1 Schematic view of a BPM with four electrodes and the coordinate system.

In case that a BPM is ideally completed, we can get the following four pairs of two-dimensional map functions by calculation,

$$x_1(\beta,\delta),\ y_1(\beta,\delta) \qquad \text{(eq. 5)}$$

$$x_2(\beta,\gamma),\ y_2(\beta,\gamma) \qquad \text{(eq. 6)}$$

$$x_3(\alpha,\gamma),\ y_3(\alpha,\gamma) \qquad \text{(eq. 7)}$$

$$x_4(\alpha,\delta),\ y_4(\alpha,\delta) \qquad \text{(eq. 8)}$$

This means that there are four ways to obtain beam positions, by use of the output voltages from three electrodes chosen out of the four electrodes. These four pairs of beam positions should coincide with each other if the BPM is ideal. When the four pairs of positions are calculated by the voltages $V1'(x,y)$, $V2'(x,y)$, $V3'(x,y)$, $V4'(x,y)$ measured by a real BPM with beam, these positions are generally different from each other. Because a real BPM has such errors as manufacturing error of the vacuum chamber, imbalance of the gain of each electrode and non-linearity of the signal processing circuit. The corrections of the voltages for these errors are generally as follows,

$$V1(x, y) = C1(x, y ; I_b, G)\ V1'(x, y) \quad \text{(eq. 9)}$$

$$V2(x, y) = C2(x, y ; I_b, G)\ V2'(x, y) \quad \text{(eq. 10)}$$

$$V3(x, y) = C3(x, y ; I_b, G)\ V3'(x, y) \quad \text{(eq. 11)}$$

$$V4(x, y) = C4(x, y ; I_b, G)\ V4'(x, y), \quad \text{(eq. 12)}$$

where I_b is the beam current and G is the gain of signal processing circuit. If x, y, I_b and G dependence of the correction functions C1, C2, C3, C4 is negligible, the corrections are performed by the following constant parameters F1, F2, F3, F4,

$$F1 \approx C1(x, y ; I_b, G) \quad \text{(eq. 13)}$$

$$F2 \approx C2(x, y ; I_b, G) \quad \text{(eq. 14)}$$

$$F3 \approx C3(x, y ; I_b, G) \quad \text{(eq. 15)}$$

$$F4 \approx C4(x, y ; I_b, G). \quad \text{(eq. 16)}$$

Since α, β, γ, δ are defined by the ratios of the voltages V1, V2, V3, V4, the constant parameters F1, F2, F3, F4 can be normalized by F1, as follows,

$$f_2 \equiv \frac{F2}{F1},\quad f_3 \equiv \frac{F3}{F1},\quad f_4 \equiv \frac{F4}{F1}. \quad \text{(eq. 17)}$$

α, β, γ, δ are reproduced by use of the measured voltages V1', V2', V3', V4' corrected by the normalized parameters f_2, f_3, f_4,

$$\alpha(x,y) = \frac{V1'(x,y) - f_2V2'(x,y)}{V1'(x,y) + f_2V2'(x,y)} \quad \text{(eq. 18)}$$

$$\beta(x,y) = \frac{f_4V4'(x,y) - f_3V3'(x,y)}{f_4V4'(x,y) + f_3V3'(x,y)} \quad \text{(eq. 19)}$$

$$\gamma(x,y) = \frac{V1'(x,y) - f_4V4'(x,y)}{V1'(x,y) + f_4V4'(x,y)} \quad \text{(eq. 20)}$$

$$\delta(x,y) = \frac{f_2V2'(x,y) - f_3V3'(x,y)}{f_2V2'(x,y) + f_3V3'(x,y)}. \quad \text{(eq. 21)}$$

Two parameters are independent in α, β, γ, δ. β and δ are derived from α and γ by elimination of parameters x, y,

$$\beta = \beta(\alpha, \gamma) \quad \text{(eq. 22)}$$

$$\delta = \delta(\alpha, \gamma). \quad \text{(eq. 23)}$$

The relationships are obtained from mapping data by a calculation. As equations 22 and 23 are satisfied regardless of beam position, the correction parameters f_2, f_3, f_4 are obtained by the method of least squares. The chi-square is defined by the pairs of (β, $\beta(\alpha, \gamma)$) and (δ, $\delta(\alpha, \gamma)$) derived from voltage data sets (V1', V2', V3', V4') at several different beam positions as follows,

$$\chi(f_2,f_3,f_4)^2 = \sum_{n=1}^{N} \left\{ \left[\beta_n - \beta(\alpha_n, \gamma_n)\right]^2 + \left[\delta_n - \delta(\alpha_n, \gamma_n)\right]^2 \right\}, \quad \text{(eq. 24)}$$

where N is the number of the beam positions. N must be more than four. The parameters f_2, f_3, f_4 can be optimized by minimizing the chi-square.

§3 Application to the BPMs of SPring-8 storage ring

The method developed in section 2 was applied to all of the 288 BPMs of SPring-8 storage ring. The electron beam was perturbed by a single dipole kick of the steering magnets to the horizontal and vertical directions. The steering magnets were excited in order as the phase of the coherent oscillation rounds at all BPMs. The amplitude of the oscillation was about 1.5mm. The typical distribution of beam positions at a BPM is shown in Fig. 2.

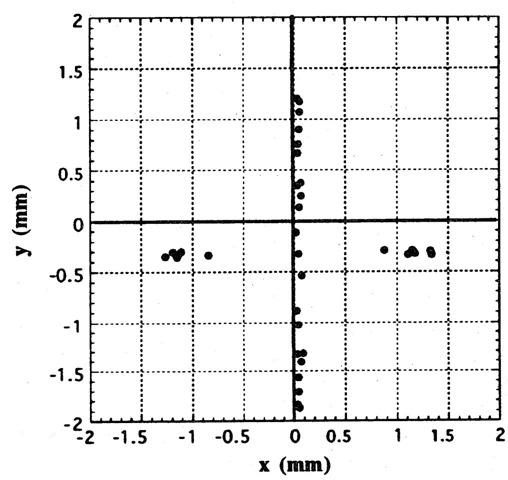

Figure 2 Typical distribution of beam positions at a BPM. There are 36 points.

The functions $\beta(\alpha, \gamma)$ and $\delta(\alpha, \gamma)$ were obtained by fitting the numerical solution of the static Laplace equation by boundary element method to seventh-orders polynomials,

$$\beta(\alpha, \gamma) = \sum_{k=0}^{7} \sum_{n=0}^{k} b_{n,k-n}\alpha^n\gamma^{k-n} \quad \text{(eq. 25)}$$

$$\delta(\alpha, \gamma) = \sum_{k=0}^{7} \sum_{n=0}^{k} d_{n,k-n}\alpha^n\gamma^{k-n}. \quad \text{(eq. 26)}$$

The chi-square (equation 24) was calculated from equations 18, 19, 20, 21, 25 and 26. The correction parameters f_2, f_3, and f_4 for each BPM were obtained by minimization of the chi-square.

The differences Δx, Δy of the four pairs of beam positions which are derived from equations 5,6,7 and 8 are defined as follows,

$$\Delta x = \max(x_1, x_2, x_3, x_4) - \min(x_1, x_2, x_3, x_4) \qquad \text{(eq. 27)}$$

$$\Delta y = \max(y_1, y_2, y_3, y_4) - \min(y_1, y_2, y_3, y_4). \qquad \text{(eq. 28)}$$

The map functions, equations 5, 6, 7 and 8, were also obtained by fitting the numerical solution of the static Laplace equation to seven-orders polynomials, for example,

$$x_1(\beta, \delta) = \sum_{k=0}^{7} \sum_{n=0}^{k} X^{(1)}_{n,k-n} \beta^n \delta^{k-n} \qquad \text{(eq. 29)}$$

$$y_1(\beta, \delta) = \sum_{k=0}^{7} \sum_{n=0}^{k} Y^{(1)}_{n,k-n} \beta^n \delta^{k-n} \qquad \text{(eq. 30)}$$

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Δx, Δy with and without the correction by f_2, f_3, f_4 are compared in Fig. 3.

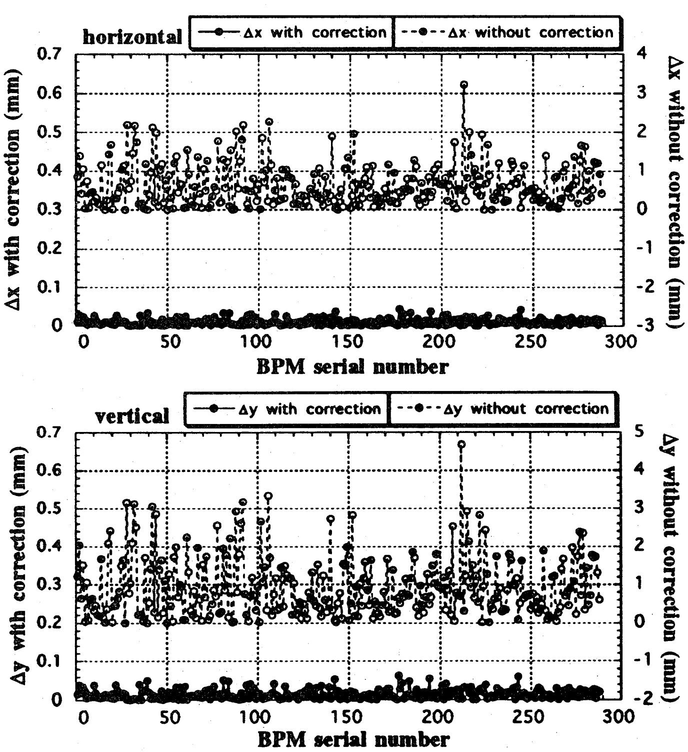

Figure 3 The comparisons between Δx, Δy with and without the corrections by parameters f_2, f_3, f_4.

Many pairs of (Δx, Δy) without the correction have values larger than a few hundreds micron, and the maximum is (3224μm, 4667μm). All of the pairs of (Δx, Δy) with the correction converge less than (44μm, 63μm). The correction parameters f_2, f_3, f_4 disperse from 0.77 to 1.30. The origin of large correction factors is mainly the reflection of beam signal in connectors of cables which connect electrodes to the signal processing circuits. The reflection is not calibrated on the off-line bench test.

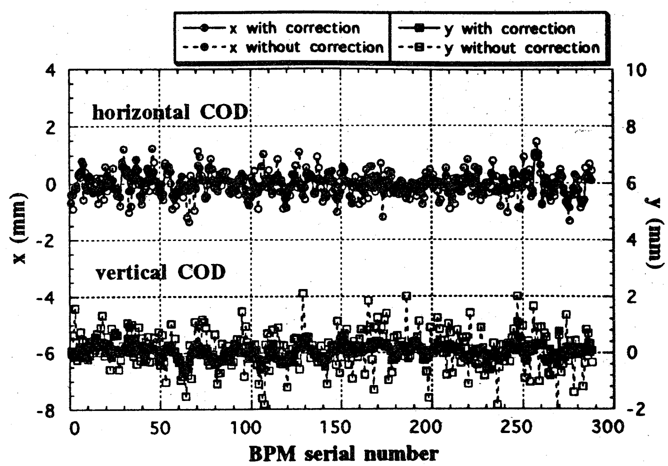

Figure 4 The comparison between CODs with and without the corrections by parameters f_2, f_3, f_4.

The comparison of the closed orbit distortions (CODs) with and without the correction is shown in Fig. 4. The CODs with the correction become remarkably smooth. The root mean squares (RMSs) of the horizontal COD with and without the correction are 0.32mm and 0.50mm, respectively. The RMSs of the vertical COD with and without the correction are 0.26mm and 0.69mm, respectively. Especially, the vertical COD was drastically improved. The vertical beam positions are more sensitive to the various errors than the horizontal positions. This is due to the allocation of the four button electrodes on the beam chamber whose cross-section is 70×40mm ellipse like.

§4 Conclusions

A method of beam-based calibration for beam position monitor was developed in the section 2. The method was applied to all of the 288 BPMs of SPring-8 storage ring. The RMS of the measured COD was improved. The improvement was mainly owing to the correction for the reflections of beam signals in connectors of cables. This method is effective in the linear corrections for BPM output voltages, however, is ineffective in the non-linear corrections, for example the non-linearity of the beam signal processing circuits. To correct the non-linearity, we have to take account of the x, y, I_b and G dependence of the correction functions C1, C2, C3, C4.

The mapping for all BPMs by an antenna or a wire spends much time and is laborious. The correction of the map will be difficult due to the different electric boundary condition from beam passing. We propose this method as a useful procedure instead of mapping by use of an antenna or a wire on the off-line.