CALIBRATION OF KEKB BEAM POSITION MONITORS

Kotaro Satoh and Masaki Tejima
KEK, High Energy Accelerator Research Organization
Oho 1-1, Tsukuba, Ibaraki 305 Japan

Abstract

This paper first proposes a practical model for output signals of BPM electrodes. The model is based on a definition of the geometric center of a BPM head, and on the assumption that the character of the head can be specified only by a small number of parameters, the relative gains of electrodes. On the basis of the model, calibration was done to find the relative gains of all KEKB LER BPM heads. The paper reports and discusses the calibration results.

1 INTRODUCTION

Stability of the closed orbit is essential for stable operations of rings, particularly of those requiring strong sextupole magnets. To stabilize the beam orbit, the first step would be to measure the beam position with respect to the design orbit, or to measure the absolute beam position. On installation of a BPM head its mechanical reference axis is alligned to the ideal orbit. For the absolute position measurement, therefore, location of the electric center, relative to the reference frame, of each BPM head must be known. This is the main reason why we need calibration of BPM heads. Here we apply a signal wire method to the calibration.

This paper first proposes a practical model for output signals of BPM electrodes, and define a geometric monitor center by assuming that each electrode has its ideal position-response function. This model also assumes that the real output signal from an electrode is proportional to its response function multiplied by a constant factor, called its gain, and that the gain is independent of the beam position [1]. We would say here that character of each head can be specified only by a small number of gains.

In a real BPM head, variation of the gains from their ideal values displaces its electric center from the ideal one. Following the present model, the calibration is to know the relative gains among electrodes of each BPM head. A least-square method estimates the gains from many output data with various wire positions. After the calibration the electric center is expected to coincide with the geometric one.

With this method the calibration of KEKB LER BPM heads is in progress. The present paper reports and discusses the results.

2 MODELING OF OUTPUT DATA

2.1 Dependence of fields on the beam position

Consider electromagnetic fields produced by a point charge moving inside a perfectly conducting uniform pipe. The

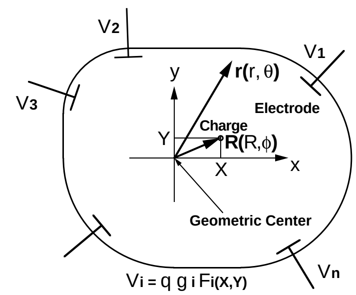

Figure 1: Coordinate system and an image of the model monitor.

point charge is moving with the light velocity along an orbit, parallel to the axis, displaced by $\mathbf{R}(X = R\cos\theta, Y = R\sin\theta)$ shown in Fig.1.

The moving charge couples only to TEM fields, whose potential is governed by a two-dimensional Laplace's equation. We consider a Green function $G_2(\mathbf{r}, \mathbf{r}')$

$$G_2(\mathbf{r}, \mathbf{r}') = -\frac{1}{2\pi}\log|\mathbf{r} - \mathbf{r}'|, \qquad (1)$$

which satisfies

$$\Delta_2 G_2(\mathbf{r}, \mathbf{r}') = -\delta_2(\mathbf{r} - \mathbf{r}'), \qquad (2)$$

where Δ_2 and $\delta_2(\mathbf{r})$ are the two-dimensional Laplacian operator and δ-function.

Then the field potential $\Phi(\mathbf{r})$ is a sum of the direct field given by the Green function, and fields $\Phi_{imag}(\mathbf{r})$ produced by the image charge on the pipe surface. With a constant K we can write

$$\Phi(\mathbf{r}) = K\log|\mathbf{r} - \mathbf{R}| + \Phi_{imag}(\mathbf{r}). \qquad (3)$$

The direct field depends on $\mathbf{R}$ as $\log|\mathbf{r} - \mathbf{R}|$, which can be expanded into a series

$$\log|\mathbf{r} - \mathbf{R}| = \log r - \sum_{k=1}\frac{1}{k}(\frac{R}{r})^k\cos k(\phi - \theta). \qquad (4)$$

Finally we have

$$\begin{aligned}\Phi(\mathbf{r}) \quad = \quad & K[(\log r - C_0(\mathbf{r})) \\ & -\sum_{k=1}\frac{1}{k}R^k\cos k\theta(\frac{\cos k\phi}{r^k} + C_k(\mathbf{r})) \\ & -\sum_{k=1}\frac{1}{k}R^k\sin k\theta(\frac{\sin k\phi}{r^k} + S_k(\mathbf{r}))], \end{aligned} \qquad (5)$$

where $C_k(\mathbf{r})$ and $S_k(\mathbf{r})$ corespond to the fields by the image charge.

Now we find that the field must be expressed as a superposition of components each of which is derived from the k-th moments of charge distribution, $R^k \cos k\theta$ and $R^k \sin k\theta$, and hence depends on the beam position (X, Y) through a special manner only with the k-th harmonic functions of X and Y.

2.2 Output signal of BPM

Electrodes of a BPM head are nothing but antennas probing the field inside the chamber, as shown in Fig.1. The output of the electrode is determined by the field strength at its location, or more precisely, the averaged field strength, with a weight function, over the electrode port. The relation between the averaged field strength and the beam position is called a position-response function. For an ideal BPM head the output of each electrode is determined only by the response function. For a real BPM, however, the output of an electrode is differed from the ideal repsonse function mainly due to stray capacitance and impedance of the vacuum feedthrough. Now we are in a position to write down a model for the output signal from the i-th electrode,

$$V_i = q g_i F_i(X, Y), \qquad (6)$$

where $F_i(X, Y)$ is the ideal position response function and is normalized by $F_i(0, 0) = 1$. The parameter q measures the strength of simulating current on the wire. The factors g_i are gains representing the signal imbalance among the electrodes. By giving each electrode its ideal response function we have just defined a geometric center so that equations (6) hold simultaneously.

We have known that $F_i(X, Y)$ can be always expanded into a series of harmonic functions of X and Y,

$$\begin{aligned} F_i(X,Y) &= 1 + \sum_{k=1} R^k (a_i(k) \cos k\theta + b_i(k) \sin k\theta) \\ &= 1 + a_i(1)X + b_i(1)Y \\ &+ a_i(2)(X^2 - Y^2) + b_i(2)(2XY) \\ &+ a_i(3)(X^3 - 3XY^2) + b_i(3)(3X^2Y - Y^3) \\ &+ \ldots \end{aligned} \qquad (7)$$

Coefficients $a_i(k)$ and $b_i(k)$ are determined by the cross-section of the BPM head and geometry of the electrode, and can be calculated with numerical methods.

Variation of performance of BPM heads is introduced not only by the impedance imbalance but also by mechanical fabrication errors. These errors produce a responce function different from the ideal one with the result of a slightly wrong position sensitivity. What we want to measure, howevere, with the BPM system is the absolute positions with respect to the ideal orbit, rather than precise position movements. This is the reason why we have adopted the present modeling of a BPM head. Even with the mechanical errors, we can define the geometric center and find its absolute position relative to the reference frame by the calibration. Moreover, considering recent mechanical fabrication technique we expect that the variation of the response function would be sufficiently small.

3 GAIN ESTIMATION

How to estimate the gains has been reported before [1]. Only a brief description for calibrating the gains is presented here. Let the number of electrode be n and the total number of the measurement be m. At each measurement the wire position is changed and the output signal of each electrode is measured. At the j-th measurement the output signal from the i-th electrode V_{ij} can be written as

$$V_{ij} = g_i q_j F_i(X_j, Y_j), \qquad (8)$$

where q_j is the signal strength of the wire, normalized by g_1=1, and X_j and Y_j are the wire position at the j-th measurement relative to the unknown geometric center. Notice that the wire impedance is dependent on its position and that the strength q_j may change at each measurement. After the m-th measurement the unknown parameters are g_2, g_3, ..., g_n, and (q_1, X_1, Y_1), ..., (q_m, X_m, Y_m) with the total number of $3m + n - 1$. On the other hand the data are (V_{11}, V_{21}, ..., V_{n1}), ..., (V_{1m}, V_{2m}, ..., V_{nm}) with the total number of $4m$. If the number of the data is larger than that of the unknown parameters, we can estimate the unknown parameters with a least square method.

4 CALIBRATION RESULTS AND DISCUSSION

We have finished the calibration of two types of circular symmetric BPM heads for the KEKB LER. One is 94 mm in diameter, and the other is 150 mm. Each BPM has 4 output ports. Signals were measured with a narrow-band detector with a center frequency of 1.018 GHz, two times the acceleration frequency.

Measurements were done with a 1mm step both in the horizontal and vertical directions, within a rectangular area of ± 10 mm(H) by ± 6 mm(V). The total number of measurement points for each BPM head is 21×13. The present analysis, however, uses only 25 data, which are sampled within the same area by 5 and 3 mm steps in the horizontal and vertical directions, respectively. The number of unknown parameters is 78 whereas that of the data is 100.

Table I shows an example of fitting results. In the analysis all the data are divided by a common factor so that V_{ij} and q_j are close to unity. The coordinates of the wire position are fixed on the reference frame of each BPM head, and the wire is set at the reference center at j=13 in Table I. We can, therefore, estimate displacements of the geometric center from the reference axis by reading X_{13} and Y_{13}.

Fig.2 displays the estimated gain g_2 of all circular BPMs of 94mm in diameter. Fig.3 shows the displacement of the geometric center from the reference axis of the BPM head. Systematic displacements of the center are explained by the fact that some heads have had their reference frames trimmed two times. The rms difference between the output and the expected output from the estimated parameters,

$$\sqrt{\sum_{i,j} (V_{ij} - g_i q_j F_i(X_j, Y_j))^2 / 4m},$$

Table 1: An example of data analysis
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g_1	g_2	g_3	g_4
1	.962	.970	.952

j	q_j	X_j(mm)	Y_j(mm)
1	.992	10.120	5.917
2	1.000	10.115	2.971
3	1.006	10.100	-.004
4	.999	10.123	-2.991
5	.994	10.168	-5.995
6	1.010	5.136	6.033
7	1.019	5.096	2.999
8	1.025	5.127	-.015
9	1.017	5.123	-3.025
10	1.018	5.118	-6.030
11	1.016	.099	5.981
12	1.027	.055	3.030
13	1.030	.107	.006
14	1.027	.074	-3.016
15	1.027	.105	-6.017
16	1.012	-4.929	5.997
17	1.022	-4.956	3.027
18	1.025	-4.942	.014
19	1.021	-4.967	-3.003
20	1.021	-4.921	-6.018
21	.995	-9.983	5.968
22	1.004	-9.941	3.017
23	1.005	-9.951	.046
24	1.004	-9.979	-2.959
25	1.001	-9.978	-5.990

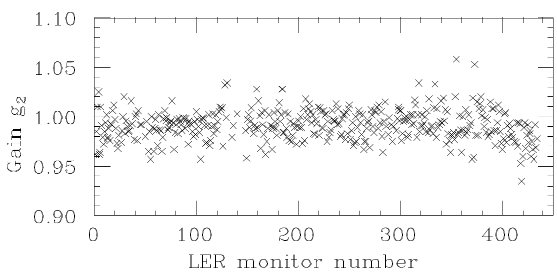

Figure 2: Estimated g_2 of all LER arc BPMs.

is summarized in Fig.4.

The rms difference, which is introduced by imperfection of the model and measurement errors, is satisfactorily small. This fact demonstrates validity of the present model and reliability of the calibration system. By analyzing the covariant matrix associated with a least square fitting we can know confidence limits of estimated parameters. Assuming that the measurement error is at most a typical rms difference of 4×10^{-4}, typical confidence limits of g_i, q_j, X_j and Y_j would be 1×10^{-3}, 5×10^{-4}, 17 μm and 11 μm, respectively.

To find X_j and Y_j we have used only ideal response functions, but have not used any information of the absolute wire positions on the calibration bed. It is, therefore, a good examination for verifying the scale of the model response function to compare the estimated wire positions and the calibrated ones. After subtracting the displacement of the geometric center, we found that the rms difference between the two sets of positions was as small as 34 μm for the case in Table I.

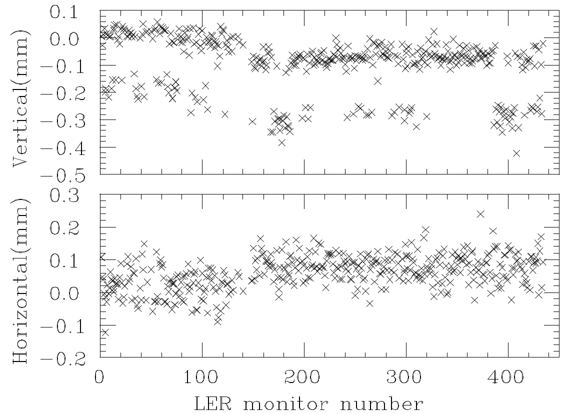

Figure 3: Displacements of the geometric center in the horizontal and vertical directions.

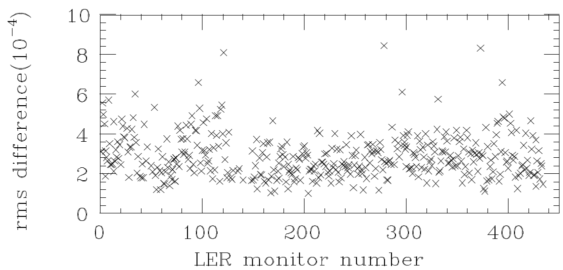

Figure 4: The rms difference of all LER arc BPMs.

Finally we close the paper with adding a comment to the geometric monitor center. In beam operations the signals from each BPM head must travel through cables, connectors, switches and so on, before reaching detectors. It is afraid that initial and long-term variations of performance of these elements break the balance of the output of each head and make its electric center wander. Fortunately enough, however, we can apply eq.(6) also to signals measured at detectors, and can expect that the performance variations contribute only to changing the gains. This observation leads an idea that the overall gains at detectors can be estimated by changing beam orbits as in the wire calibration method. We are now in a position to emphasize that the geometic center defined here is stable with respect to the reference frame of each head, and that the center position can be searched by re-calibration with beams [1].

5 REFERENCES

[1] K. Satoh and M. Tejima, Recalibration of position monitors with beams, Proceedings of 1995 Particle Accelerator Conference, Dallas, Texas.