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PRECISE POSITION MEASUREMENT BY ANALYZING THE CORRELATION BETWEEN ELECTRODES OF A SINGLE BPM*

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Abstract

Beam position is one of the most important parameters in a particle accelerator. The more accurate and precise the measurement system is, the more features of the beam dynamics could be revealed. A method called model-independent analysis (MIA) takes advantage of multiple beam position monitors (BPM) on the storage ring to obtain the actual beam positions by removing the random noise of each BPM. Inspired by MIA, the original voltage waveforms obtained from the electrodes of a single BPM can also be decomposed to get the beam position information. This article discusses the results of the experiments and the evaluation of the performance of the BPM at the Shanghai Institute of Applied Physics.

INTRODUCTION

BPMs are commonly used in modern light sources. The calculations and the simulations of the electrodes have already been studied. Although the fabrications are mature, the individual differences in frequency response are inevitable. Nevertheless, the impedance matchings along the cables are difficult. Thus, the original signals from different electrodes are slight different, and these signals have been mixed with parts of their reflected ones. If we still use the traditional signal processing procedures, systematic errors will be introduced in the measurements.

The induced signal from the ith electrode can be written as:

$$V_i(t) = p_i(x) \cdot Q(t) * U_i(t), \tag{1}$$

where $p_i(x)$ is the position factor, $Q(t)$ is the bunch charge distribution factor and $U_i(t)$ is the impulse voltage response. Ideally, the responses $U_i(s)$'s are identical, so the linear approximation of a two-pickup BPM is

$$V_1 \simeq (1 + K_x \cdot x) \cdot K_q \cdot q \cdot U_0, \tag{2}$$
$$V_2 \simeq (1 - K_x \cdot x) \cdot K_q \cdot q \cdot U_0. \tag{3}$$

Thus, the position of the bunch is

$$x \simeq \frac{1}{K_x} \frac{V_1 - V_2}{V_1 + V_2}. \tag{4}$$

Including the response deviations and the random noises, the final signals are

$$V_1 \simeq (1 + K_x \cdot x) \cdot K_q \cdot q \cdot (U_0 + \Delta_1) + N_1, \tag{5}$$
$$V_2 \simeq (1 - K_x \cdot x) \cdot K_q \cdot q \cdot (U_0 + \Delta_2) + N_2. \tag{6}$$

The best linear approximation for the calculated position (higher order terms like $N_1 \cdot N_2$ or $\Delta_1 \cdot N_1$ have also been omitted after the Taylor expansion) will be

$$\begin{aligned}
&\frac{V_1 - V_2}{V_1 + V_2} \\
=&\frac{K_x x K_q q(2U_0 + \Delta_1 + \Delta_2) + K_q q(\Delta_1 - \Delta_2) + N_1 - N_2}{K_q q(2U_0 + \Delta_1 + \Delta_2) + K_x x K_q q(\Delta_1 - \Delta_2) + N_1 + N_2} \\
\simeq&K_x \cdot x \\
&- \frac{K_x^2 x^2 - 1}{2U_0 + \Delta_1 + \Delta_2} \cdot (\Delta_1 - \Delta_2) \\
&+ \frac{K_x \cdot x - 1}{K_q \cdot q \cdot (2U_0 + \Delta_1 + \Delta_2)} \cdot N_1 \\
&+ \frac{K_x \cdot x + 1}{K_q \cdot q \cdot (2U_0 + \Delta_1 + \Delta_2)} \cdot N_2.
\end{aligned} \tag{7}$$

The system resolution can only be improved by removing the last three terms of the r.h.s. of the above equation.

MODE SEPARATION

The area of the envelope of the signal is used in Equation (4) to minimize the influences of the random noise and the lag differences between cables. This method will improve the accuracy of the measurement, but the response differences between electrodes and the reflection in the cable are still there. Since these response deviations, signal reflections and random noises are linearly mixed into the final signal in Equations (5) and (6), a singular value decomposition (SVD) can potentially separate them as different modes. [1,2]

Rather than calculating the integrals of the envelopes of the raw ADC waveforms, We will create a waveform matrix and the SVD of the matrix will give several—as many as the number of electrodes—modes, some of which are, hopefully, unrelated to Δ_1, Δ_2, N_1 or N_2. The spatial vectors of the U_0-related mode(s) will be used to calculate the bunch position.

Since the signals are narrow-banded sine waves, there will be two principal components we're interested in: a $\sin \omega t$ mode and a $\cos \omega t$ mode. The rest modes can all be regarded

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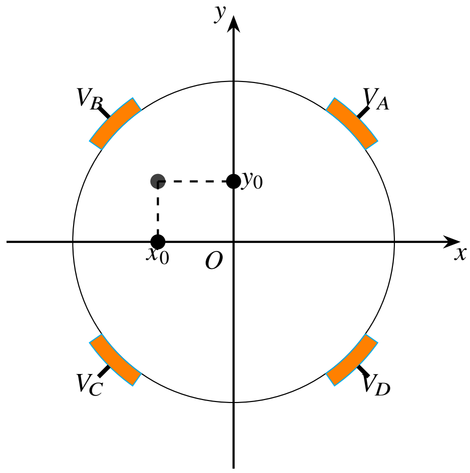

Figure 1: The 4-pickup BPM layout.

as noise modes. The result of the SVD may look like:

$$\begin{aligned}
&\begin{pmatrix} V_1(t) & V_2(t) & \cdots & V_n(t) \end{pmatrix}_{m\times n} \\
&= \begin{pmatrix} u_{\sin}(t) & u_{\cos}(t) & u_{\text{noise},1}(t) & \cdots & u_{\text{noise},m-2}(t) \end{pmatrix}_{m\times m} \\
&\quad \times \operatorname{diag}(s_{\sin}, s_{\cos}, \ldots, s_n)_{m\times n} \\
&\quad \times \begin{pmatrix} v_{\sin}(i) & v_{\cos}(i) & v_{\text{noise},1}(i) & \cdots & v_{\text{noise},n-2}(i) \end{pmatrix}^T_{n\times n}
\end{aligned} \tag{8}$$

The Pythagorean additions of the corresponding spatial vectors $\sqrt{(s_{\sin}v_{\sin})^2 + (s_{\cos}v_{\cos})^2}$ are proportional to the induced signal strength V_i's and can be used in (4) to get the beam positions. For example, the horizontal position measured with a four-pickup BPM (as shown in Figure 1) can be written as:

$$x = \frac{1}{K_x}\frac{V_A + V_D - V_B - V_C}{V_A + V_B + V_C + V_D}, \tag{9}$$

where $V_i = \sqrt{(s_1 v_1(i))^2 + (s_2 v_2(i))^2}$.

SIMULATIONS

After collecting signals from different electrodes in actual measurements, we selected one of the reflection-free waveforms as a perfect input $u_0(t)$ (the blue line in Figure 2). To simulate a normal four-pickup BPM, a predefined position was chosen and the scales of the signals from the electrodes were calculated. Delayed and scaled waveform $\beta u_0(t-\tau)$ (the red, dashed line in Figure 2) was added to the signals to simulate the imperfection of the transmission. Different narrow-band signals were used to simulate the response differences between electrodes. Random noises were also added to simulate other disturbances, such as ADC truncation errors. The 4 final signals (as shown in Figure 3) were generated as:

$$\begin{aligned}
V_A(t) =& (1 + K_x\cdot x_0 + K_y\cdot y_0)(u_0(t) + \alpha_1 n_1(t)) \\
&+ \beta_1 u_0(t-\tau_1) + \gamma n_{\text{random}}(t), \qquad (10)\\
V_B(t) =& (1 - K_x\cdot x_0 + K_y\cdot y_0)(u_0(t-t_2) + \alpha_2 n_2(t)) \\
&+ \beta_2 u_0(t-\tau_2) + \gamma n_{\text{random}}(t), \qquad (11)\\
V_C(t) =& (1 - K_x\cdot x_0 - K_y\cdot y_0)(u_0(t-t_3) + \alpha_3 n_3(t)) \\
&+ \beta_3 u_0(t-\tau_3) + \gamma n_{\text{random}}(t), \qquad (12)\\
V_D(t) =& (1 + K_x\cdot x_0 - K_y\cdot y_0)(u_0(t-t_4) + \alpha_4 n_4(t)) \\
&+ \beta_4 u_0(t-\tau_4) + \gamma n_{\text{random}}(t), \qquad (13)
\end{aligned}$$

where (x_0, y_0) is the coordinate of the beam, $n_i(t)$'s are narrow-band noises, $n_{\text{random}}(t)$ is the random noise and K_x, K_y, α_i's, β_i's and γ are constants. These signals will be used to evaluate the validation of the SVD method, to estimate the performances of different methods, and to compare the accuracies of different algorithms.

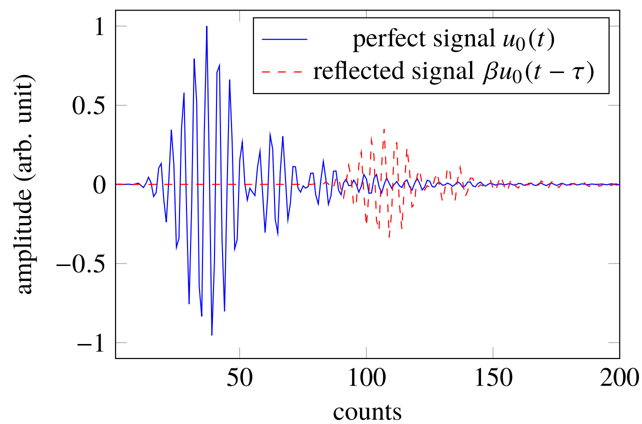

Figure 2: Samples from real measurements and its shifted, scaled reflection signal.

Traditionally, the signal strength in Equation (4) was obtained by adding up the absolute values of all sample points. This algorithm is a little sensitive to the sampling phase if the sampling rate is not high enough. The in-phase and quadrature components of the signal are robuster, so we chose the Hilbert transformation as another competitive algorithm.

The random reflections and noises were recursively generated and randomly contributed to the "perfect signals." The positions were calculated using equation (4) in which the signal amplitudes were obtained with the aforementioned algorithms:

1. the sum of the absolute values along the waveform;
2. the sum of the absolute values of the Hilbert transformation of the signal;
3. and the Pythagorean addition of the spatial vectors of the SVD results.

The chosen coordinate and the results of the simulation are shown in Table 1.

As can be seen, the mean values and the standard deviations of the first two results are very close. This is because the two algorithms are basically the same idea, except for

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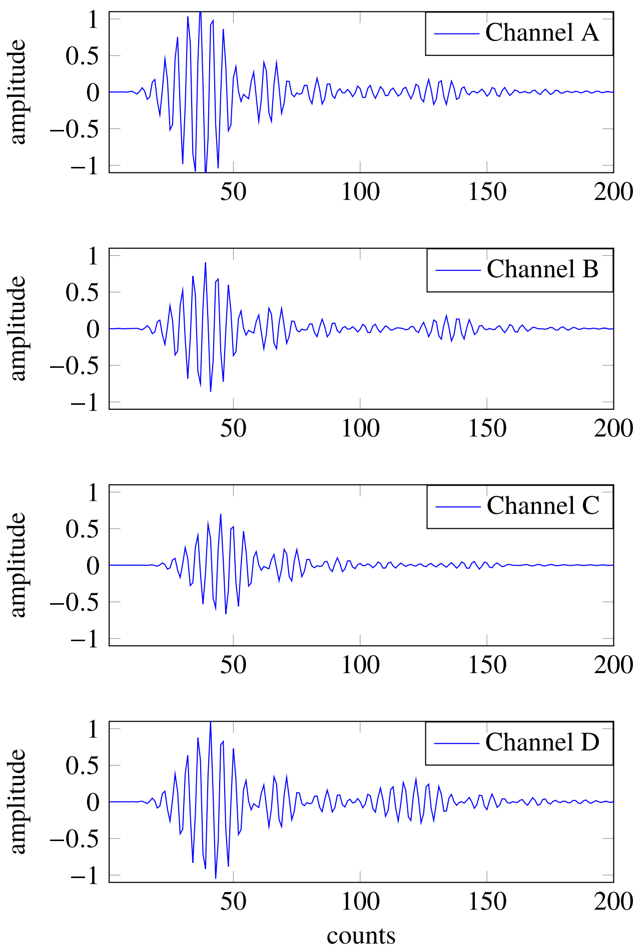

Figure 3: Signals were calculated with the following parameters: $K_x = K_y = 1$, $(x_0, y_0) = (0.2, 0.1)$, and other time lags and coefficients were randomly chosen at exaggerated intervals to amplify the measurement errors.

some detailed optimization. The sum method is slightly more accurate than the Hilbert method. The reason is that the Hilbert transformation always gives a positive-definite noise envelope, while the expected value of the noise in sum method is zero. The sampling rate is adequately fast so the variances of the positions in the sum method do not visibly different from those in the Hilbert method.

The SVD method, on the other hand, has a great advantage in both the accuracy and the resolution measurements, simply because the common part of the responses of the electrodes were mostly extracted. Hence, no disturbances were introduced when using Equation (4).

CONCLUSION

The inconsistencies in the electrodes, the imperfection of the transmission cables and the pervasive random noises will contaminate the accuracy and the resolution of the position measurement system when no extra processing is applied. This article has studied the possibility to get rid of these environmental defect without upgrading the hardware.

Table 1: Performance Comparison between Different Algorithms

Algorithm	Parameter	Value
definition	x_0	0.2
	y_0	0.1
sum	$\bar{x}$	0.1705
	$\lvert\Delta x\rvert/x_0$	14.75 %
	std(x)	0.0484
	$\bar{y}$	0.0916
	$\lvert\Delta y\rvert/y_0$	8.4 %
	std(y)	0.0517
Hilbert	$\bar{x}$	0.1703
	$\lvert\Delta x\rvert/x_0$	14.85 %
	std(x)	0.0484
	$\bar{y}$	0.0914
	$\lvert\Delta y\rvert/y_0$	8.6 %
	std(y)	0.0517
SVD	$\bar{x}$	0.2010
	$\lvert\Delta x\rvert/x_0$	0.5 %
	std(x)	0.0103
	$\bar{y}$	0.1067
	$\lvert\Delta y\rvert/y_0$	6.7 %
	std(y)	0.0073

CONCLUSION

The inconsistencies in the electrodes, the imperfection of the transmission cables and the pervasive random noises will contaminate the accuracy and the resolution of the position measurement system when no extra processing is applied. This article has studied the possibility to get rid of these environmental defect without upgrading the hardware.

The SVD method was used to find the global modes which are related to the beam position. Simulations have been made to estimate the performance of this method. As comparisons, the traditional methods have also been evaluated using the same set of signals. As a satisfying result, the SVD method has obvious superiority in both accuracy and resolution. The relative errors and the standard deviations have been improved by almost one order of magnitude when using the new method.

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