CAVITY BPM PERFORMANCE ONLINE EVALUATION USING PCA METHOD*

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Abstract

This article proposes a new test method to evaluate the performance of cavity beam position monitors using the actual beam as the exciting signal. The new method separates the signals of different modes and improves the measurement accuracy by eliminating unwanted couplings from other sources.

INTRODUCTION

Cavity beam position monitors (CBPM) are an important beam diagnostic device for free electron laser facilities. CBPMs can be used to measure a lot of bunch parameters based on versatile modes, some of which are bunch charge, transverse position and bunch length. Their performances need to be evaluated before they're officially used. Traditionally, CBPM performances are evaluated by measuring the network parameters by using a network analyzer. But an online test with real beam is always appreciated.

This CBPM component consists of two adjacent cavities: a reference cavity followed by a position cavity. The reference cavity is used to measure the bunch charge (normalization factor) by extracting the TM_{010} mode and the position cavity measures the horizontal and the vertical components of the TM_{110} mode, i.e., the position of the bunch.

In order to precisely measure the electron beam position in the undulator section CBPM system will be employed by Shanghai soft-Xray Free Electron Laster (SXFEL) test facility. Sub-micron resolution with 0.5 nC bunch is required [1]. To satisfy this demand a set of low-Q cavity sensors and a set of high-Q cavity sensors have been developed and tested with ~30 pC beam using SDUV FEL test facility.

Figure 1: CBPM on movement platform.

To study the position dependence of the output signals from the cavities, a movement platform is introduced to control the transverse displacement of the CBPM (as shown in Fig.1). The movement platform is controlled with a stepper motor so that bunches at different positions can be generated at will. The output signals from the two cavities are recorded in three channels of an oscilloscope simultaneously: reference signal from the reference cavity, and horizontal and vertical signals from the position cavity.

MODE SEPARATION

The electromagnetic field in a cavity is a linear combination of orthogonal modes determined by the property of the cavity: $V(t) = \sum_{m,n,p} C_{m,n,p}V_{m,n,p}(t) + C_{noise}V_{noise}(t)$. The principle component analysis method (PCA) is good at separating the modes by using enough samples of measurements.[2,3]

The goal of using PCA on the raw signals from the electrodes is to decompose the main mode, the leaked/coupled modes and stochastic noises. The temporal vectors correspond to $V_{m,n,p}(t)$, so the time evolution properties of the modes can be studied separately, such as the resonant frequencies and the quality factors (damping ratio). These properties will be used to determine the physical source of the mode and, furthermore, to optimize the signal processing if possible. The spatial vectors corresponding to the (normalized) $C_{m,n,p}$ indicate the variance in the amplitude during the measurements. These vectors are especially useful when the number of independent variables are much less than the rank of the data matrix. In this test, the only obvious variables are the position of the beam, the bunch charge and the bunch length. We will only initiate the change of the position of the beam by moving the platform, but the charge and the length of the bunch can still jiggle.

Signals from the Reference Cavity

Using PCA on the signal matrix from the reference cavity when the beams passed through the cavity with different horizontal displacement gives the main TM_{010} mode with some negligible higher order modes and random noises (as shown in Fig. 2 (a)). The spatial modes (as shown in Fig. 2 (c)) indicate that theses modes are all beam-position independent, so they are azimuth independent and can be expressed as $TM_{0,n,p}$ modes.

Based on the spectra of the temporal vectors (as shown in Fig. 2 (b)), all the modes can be regarded as random noises except for the first five ones. The quality factor ($Q = 142$) and the resonant frequency ($f_{ref,010} = 4.70$ GHz) of

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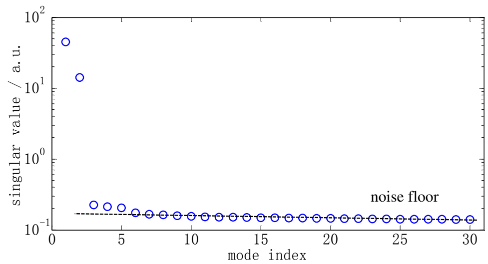
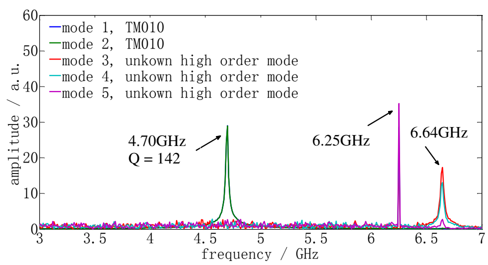
the first two modes implies that they are the two bases of the TM_{010} mode of the reference cavity. The third, the fourth and the fifth modes, although seems to be actually related to the cavity physics, have relatively small singular values and the resonant frequencies (6.25 GHz and 6.64 GHz) are far away from the interested TM_{010} mode, so they can also be regarded as normal noises.

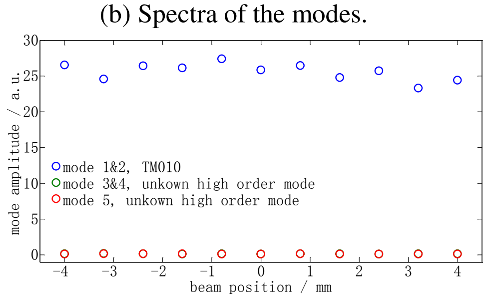
The spectrum of the first two modes determines the accurate resonant frequency of the cavity that maximizes the signal-noise-ratio.



(a) Singular values of the modes.



(b) Spectra of the modes.



(c) Temporal distribution (beam-position dependency) of the first five modes.

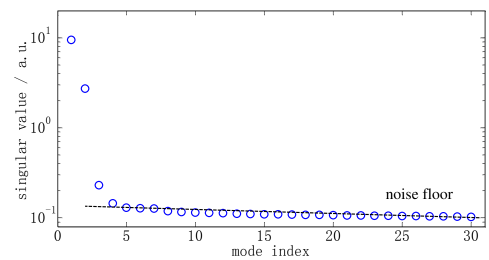
Figure 2: PCA result of the reference cavity signals.

Signals from the Position Cavity

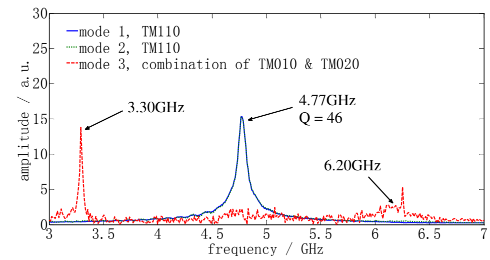
The position cavity outputs two channels: the horizontal mode signal (x-signal) and the vertical mode signal (y-signal). They are analyzed separately by changing the beam positions on different directions.

The x-signal consists of three “meaningful” modes (as shown in Fig. 3). The first two modes are linearly related to the horizontal position of the beam and the resonant frequencies, so they are the two bases of the TM_{110} mode ($f_{x,110}$ = 4.77 GHz) of the position cavity. The third mode is not related to the beam position and it's a mix of the TM_{010} mode ($f_{pos,010}$ = 3.30 GHz) and the TM_{020} mode ($f_{pos,020}$ = 6.20 GHz) of the position cavity. The resonant frequencies of this mix mode are far away from that of the main mode, so this mode can also be considered as normal noise.

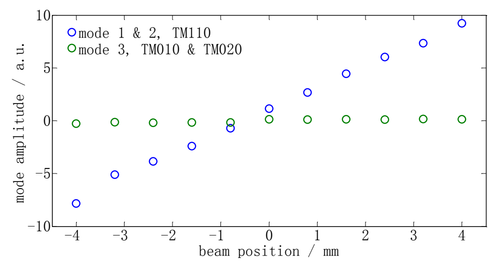
The y-signal can also be decomposed similarly (as shown in Fig. 4). The first two modes are proportional to



(a) Singular values of the modes.

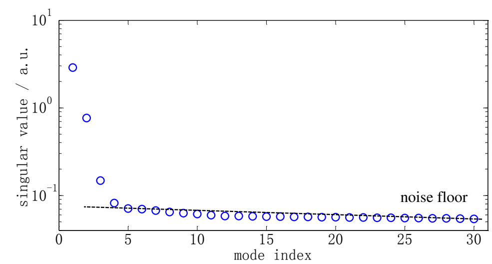


(b) Spectra of the first three modes.

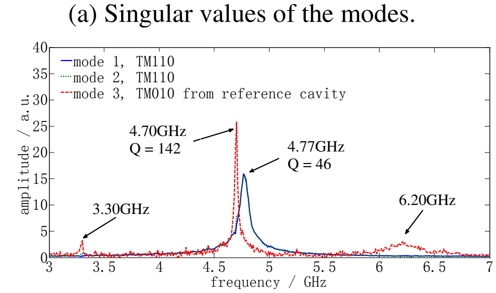


(c) Temporal distribution of the first three modes.

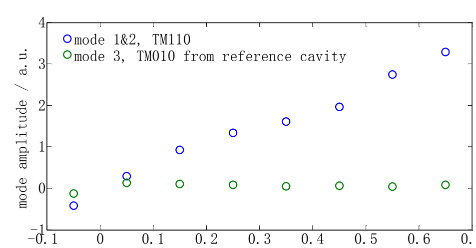
Figure 3: PCA result of the x-signal.



(a) Singular values of the modes.



(b) Spectra of the first three modes.



(c) Temporal distribution of the first three modes.

Figure 4: PCA result of the y-signal.

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the vertical position of the beam and are the two bases of the TM_{110} mode ($f_{y,110}$ = 4.77 GHz). The third mode is also unrelated to the beam position like the x-signal case. This mode, on the other hand, consists not only the TM010 mode and the TM020 mode of the position cavity, but also a stronger mode whose resonant frequency and quality factor are 4.70 GHz and 142 respectively. The frequency of the mode is close to that of the TM_{110} mode and should be treated carefully.

PERFORMANCE EVALUATION

The properties of the newly introduced mode in the y-signal match the TM_{010} mode of the reference cavity. It is reasonable to assume that the signal comes somehow from the reference cavity through the waveguide between the reference cavity and the position cavity due to some broken symmetry on the vertical direction.

Although the origin of the mode is currently a mystery, we can still assess the effect on the measurement results.

The amplitude of the TM_{110} mode at its resonant frequency is proportional to the vertical displacement of the beam, so we fit a straight line to the beam position data and the amplitude data at the working frequency f = 4.77 GHz, and find its slope, which is k = 0.0087 μm^{-1}(as shown in Fig. 5).

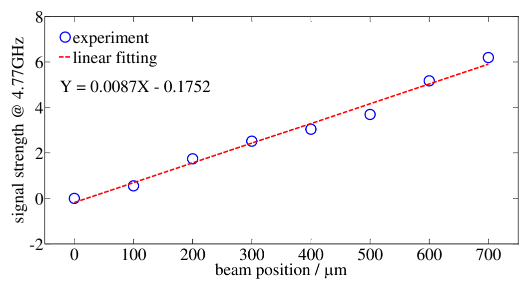

Figure 5: Linear relation between the beam position and the amplitude of the TM010 mode.

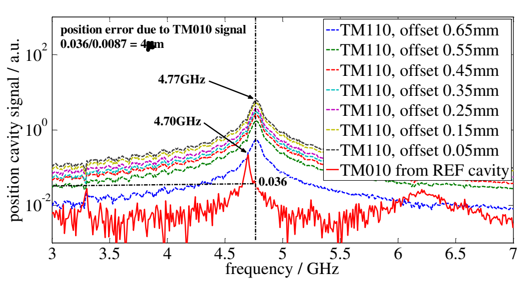

Figure 6: Amplitudes of the TM110 mode of the position cavity and the disturbance mode from the TM010 mode of the reference cavity.

After separating the modes and applying the Fourier transformation on them, the amplitudes of the principal mode and the disturbance mode at the working frequency 4.77 GHz can be calculated. The disturbance mode is unrelated to the beam position and its amplitude is always about 0.0036. The contribution of this mode in a position measurement would be at most 4 μm (by using the coefficient k = 0.0087 μm^{-1}, as shown in Fig. 6).

Since the disturbance mode has a fixed initial phase in every measurement, the position can be recovered by shifting a constant in the complex spectrum space.

FURTHER PLANS

This experiment shows that the interesting coupling of the two cavities happened only on the vertical direction. Manufacturing is blamed on this issue before we can find more evidences about the source.

More variables, such as the bunch length and the transverse size, will be introduced in future experiments to give a full evaluation of the CBPM. The movement platform will provide a rotating operation to study the horizontal-vertical cross-talk.

CONCLUSIONS

The beam based evaluation of the CBPM shows that the PCA method is a powerful tool to separate the noise from the physical mode of interest and give confident results.

This test took advantage of the movement platform to build an environment that the beam position could vary continuously without changing the status of the whole accelerator.

By decomposing the RF signal matrix directly from the electrodes, modes which are linearly correlated to the beam position and modes which are independent of the beam position can be separated, identified and analyzed.

The performance evaluation of the low-Q CBPM prototype shows that:

- The resonant frequencies and the quality factors of the reference cavity and the position cavity roughly match the MAFIA simulation of the design.
- The manufacturing of the cavities is acceptable, but there is still room for improvement.
- The contribution of the disturbance signal coupled from the TM_{010} mode of the reference cavity was no more than 4 μm.
- The disturbance signal can be eliminated entirely due to its fixed initial phase.

More experiments will be made in the future to study the effects of the bunch charge, the beam emittance and the angular alignment error.

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