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Design and construction of a multi-sensor position monitoring system applied to key components of synchrotron sources

Wei Wang[1] · Zheng Tang[1] · Xiao-Ye He[1] · Qiang Zhang[1]

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Abstracts High-accuracy position monitoring of key components is required for modern synchrotron sources, such as free-electron lasers and diffraction-limited storage rings. Although various position monitoring sensors have been adopted to monitor the displacement of key components in each direction in real time, these monitoring systems are usually based on their own coordinate system. Data from such systems are meaningful when evaluating and examining the data from each positioning monitoring system in a unified coordinate system. This paper presents the design and construction of a multi-sensor position monitoring system (MPMS). A hydrostatic levelling system, a wire position sensor (WPS) and a tiltmeter are fixed to a stainless steel plate that has been calibrated by a coordinate-measurement machine. Several plates form the MPMS. The system must compensate for the sag of the stretched wires so that the WPSs create a straight line. The method of the coordinate transformation from the sensor coordinate system to the MPMS coordinate system was thoroughly studied. An experimental MPMS that includes five plates was setup in a 20-m tunnel, and a validation study to verify fully the feasibility of the MPMS was performed.

Keywords Accelerator · Hydrostatic levelling system · Wire position sensor · Tiltmeter · Multi-sensor position monitoring system · Unified coordinate system

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✉ Xiao-Ye He
xyhe@ustc.edu.cn

[1] University of Science and Technology of China, Hefei 230029, China

1 Introduction

Recently, with the development of modern synchrotron sources represented by free-electron lasers (FELs) and diffraction-limited storage rings, high-accuracy position monitoring of key components is required. Various position monitoring sensors have been adopted to monitor in real time the displacement of components in each direction [1]. Currently, these position monitoring sensors include a hydrostatic levelling system (HLS) to monitor the vertical displacement, a wire position sensor (WPS) to monitor the horizontal and vertical displacements simultaneously, and a tiltmeter to monitor the pitch and roll angles. So far, all these monitoring sensors are usually based on their own coordinate system [2]. While each of these sensors has different monitoring ranges (for example, the monitoring range can reach to hundreds of metres in the HLS, no more than 50 metres in the WPS and only one unit or part by the tiltmeter). It is meaningful to evaluate and examine data from each position monitoring sensor in a unified coordinate system, which can be achieved by using a multi-sensor position monitoring system (MPMS) installed on the same girder with key components [3].

Currently, research is limited in this field, and only the alignment team at CERN performs relevant research. For their Compact Linear Collider (CLIC) project, they use multiple measurement sensors in the CERN laboratory to monitor the key components in real time and convert these monitoring data to the accelerator coordinate system by using a coordinate transformation, and then perform some necessary adjustments to the accelerator facility. They hope to increase significantly the efficiency of deformation monitoring. Nevertheless, this work is still just a theory because of the limited experiments and verification based on the Monte Carlo simulations [4–6].

Based on the work by CERN and combining the previous research results of the National Synchrotron Radiation Laboratory (NSRL), we design and construct a MPMS. An HLS, a WPS and a tiltmeter are fixed to a stainless steel plate. A coordinate-measurement machine (CMM) calibrated the plate to establish the coordinate system. Several plates constitute the MPMS, and the system compensates for the sag of the stretched wires to create a straight line by the WPSs. The coordinate transformation from the sensor coordinate system to the MPMS coordinate system is thoroughly studied. An experimental MPMS that includes five plates was setup in a 20-m tunnel of NSRL to test its feasibility.

2 Design of the MPMS

The MPMS includes three types of position sensors, i.e. an HLS, a WPS and a tiltmeter. These sensors will be fixed to a plate made of stainless steel, which has a coefficient of thermal expansion of 10.1 ppm K^{-1}. The plate is considered as an undeformable object, and the relative positions and orientations of the sensors are constant in the laboratory environment [7]. These plates will be installed on the same girders with these key components to simultaneously monitor the deformations in four directions, i.e. horizontal, vertical, pitch and roll deformations. The accuracy of the measurement in the vertical direction can be verified by making a comparison between the HLS and the WPS, and the tiltmeter offers a vertical compensation.

Several sensor plates are linked to be a MPMS by combining the HLSs and the WPSs in the range of 50 m. We plan to set up five sensor plates in a 20-m tunnel to construct the system. These plates will be distributed along the existing HLS system, and expansion bolts are used to fix them (Fig. 1).

The HLS is based on the mechanism of the connected vessels. A charged-coupled device (CCD) optical HLS is suitable for the MPMS, and it provides accuracy in the vertical direction [8]. A WPS measures the displacement of the sensor with respect to a stretched wire, which serves as a straightness reference. Horizontal and vertical movements can be measured simultaneously. The American OSI Company designs and develops an optical WPS (oWPS) that provides a 5-μm absolute accuracy across a 10 mm × 10 mm dynamic range [9]. A tiltmeter monitors the rotation of the sensor plate. A double-axis tiltmeter provides the pitch and roll angle monitoring. The tiltmeter sensors used in the MPMS are manufactured by the BEWIS Company, and the sensors provide a 0.0005° resolution and a 0.001° absolute accuracy (Fig. 2). The wires used with the WPS are made of Vectran fibres, which are strong and light, and the sag at 100 m is only 5.1 mm [10].

First, because the accelerator longitudinal (*Z*-axis) alignment specifications are less critical, it is not necessary to dispose of the high-precision values for the longitudinal position. Additionally, the yaw of these plates in the MPMS coordinate system is less critical. According to the simulation results, these parameters can be deduced from the usual alignment method within 0.2 mm and 1 mrad standard deviations for the longitudinal displacement and the yaw, respectively [11].

Second, each plate supports one tiltmeter from which the roll and pitch can be deduced. The pitch and roll of the plates greatly influence the measurement data of the HLS and the WPS in the vertical direction. A tiltmeter is necessary to compensate for the differences of measuring data by the HLSs and WPSs, and the differences are caused by the pitch and roll of the plates and measurement errors. We assume that the distance between the HLS to the WPS is a and b as shown in Fig. 3. (a) The differences between the HLS and the WPS are only from the measurement errors when the plates are kept level. (b) The differences between the HLS and the WPS include rotation errors of $a \cdot \sin z$ when the plates rotate around the *Z*-axis. (c) The differences between the HLS and the WPS include rotation errors of $b \cdot \sin x$ when the plates rotate around the *X*-axis (Fig. 3).

Finally, the Vectran wire and the hydrostatic surface are measured for the different sensor plates. These measurement data offer the coordinate transformation parameters that are used to transform the monitoring point coordinate from the coordinate system of sensor plates to the MPMS unified coordinate system [12]. The transformation parameters from the plate coordinate systems to the MPMS coordinate system include three shift parameters and three rotation parameters. Four parameters can be obtained by the MPMS sensors, and the remaining two are constant.

3 Construction of the MPMS

Calibration is necessary to ensure the measurement accuracy of these sensors before constructing the MPMS. A design of this plate and mechanical support equipment is developed and updated multiple times based on the shapes and weight of these sensors. The thickness of these plates and the diameter of the support pillars are 10 mm to keep

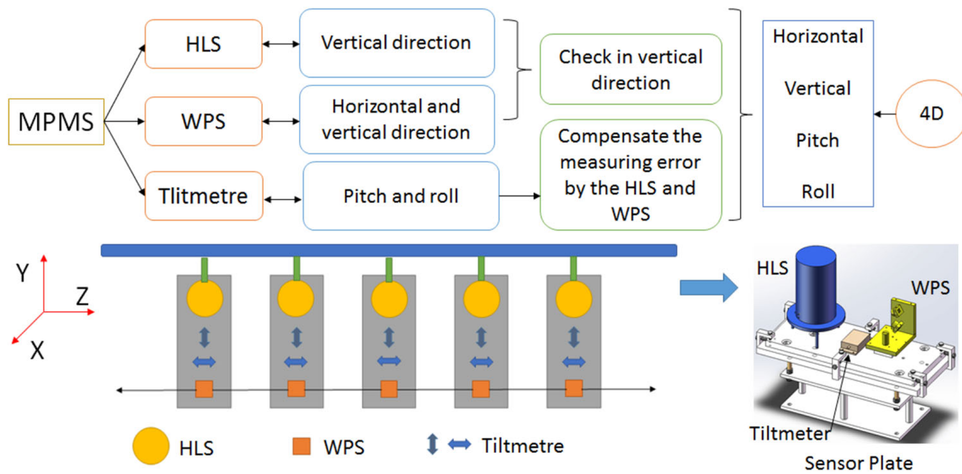

Fig. 1 Design of the MPMS

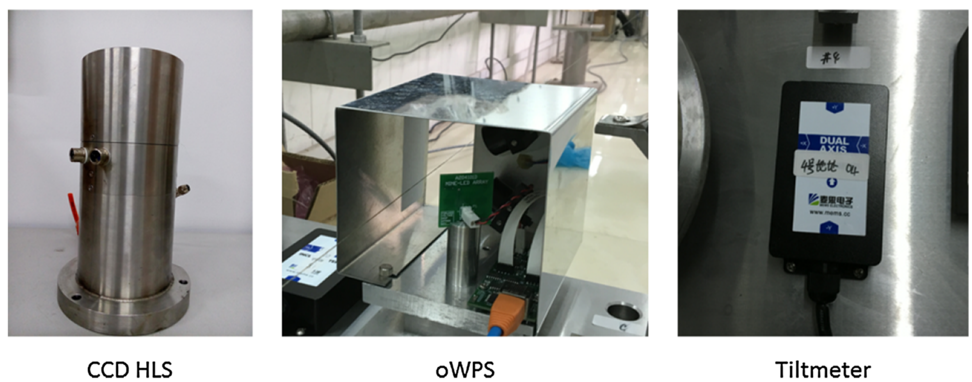

Fig. 2 Sensor types

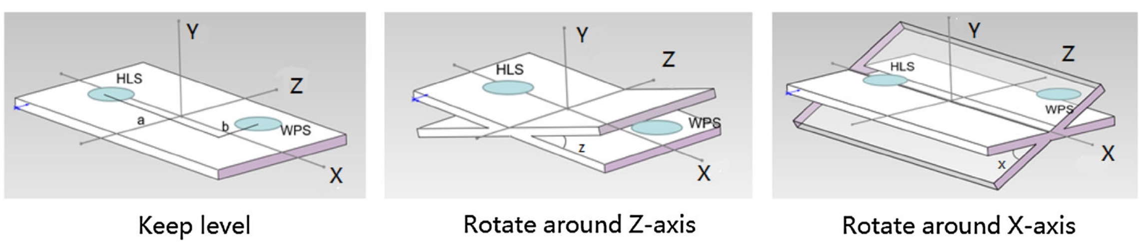

Fig. 3 Rotation effects of these plates

the system stable when all the sensors are attached on them. Six holes that can support 1.5 inches diameter survey reflectors are distributed on these plates. These holes establish the plate coordinate system and to ensure the relationship between the sensors on that plate. Screws affix the sensors to the plate. The mechanical support equipment includes a load support, an adjusting mechanism and a plate fixed mechanism (Fig. 4).

3.1 Establishment of the plate coordinate system

The plates are measured via a CMM with a 6-μm uncertainty (2σ). The CMM provides the plate coordinates of the 1.5-inch-diameter survey reflectors (see Fig. 5). A plate is fitted with the points A, B, C, D and O. We use OB as the *X*-axis and OA as the *Z*-axis. The line from O point, parallel with the external normal of the plane, is considered to be the *Y*-axis. Meanwhile, the CMM obtains the relative position of these holes and that of the screw holes (Fig. 5).

3.2 Establishment and transformation of the sensors coordinate system

The establishment of the HLS coordinate system is based at point $D(x_D, y_D, z_D)$ of the plate. The first record h_0 of the HLS is considered to be the datum reference, and the following data are recorded as h. The difference $\Delta h = h_0 - h$ is the displacement of the HLS in the vertical

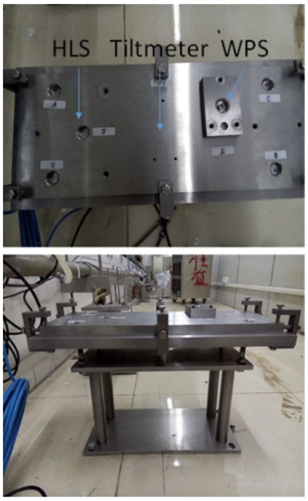

Fig. 4 Structure of the plates and the mechanical supports

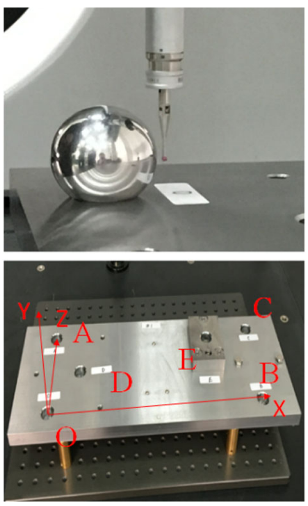

Fig. 5 Construction of the plate coordinate system

direction, and therefore, the coordinate value of the HLS is (x_D, y_D, $z_D + \Delta h$).

Simultaneously, three 6.35-mm-diameter ceramic balls are used to establish the WPS coordinate system. The centres of the ball *o* are considered to be the coordinate origin of the WPS. The normal of the plane that is constructed by the three balls is considered to be the *Y*-axis. The line from ball *o* to the midpoint between ball *a* and ball *b* is considered to be the *Z*-axis. The ball *o* gives the position of the sensor. Because it is free along an axis, ball *a* determines the pitch and yaw. As *b* is in contact with a surface, it determines the last degree of freedom of the sensor, i.e. the roll. The interface coordinate system is built with respect to the kinematic effects of each point [13] (Fig. 6).

The tiltmeter monitors the rotation of the plate, and it is not necessary to construct a coordinate system for the tiltmeter.

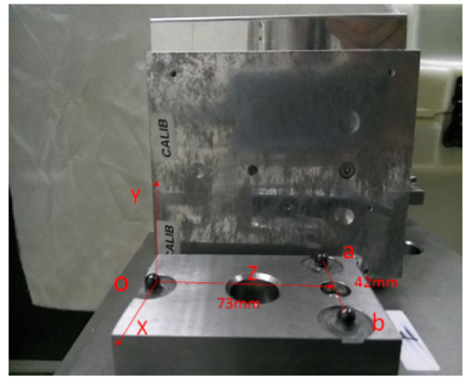

Fig. 6 WPS coordinate system based on 3 balls

The coordinate systems of the HLS and of the WPS can be transformed into the plate coordinate system by spatial analyser (SA) software based on the results of the CMM.

3.3 Construction of the MPMS and the establishment of its coordinate system

We set up an experimental MPMS in the NSRL tunnel, which is 20 m long and 2 m wide. The supports are distributed along the existing HLS system, and expansion bolts are used to fix them. An N3 level and a DL10 spirit level ensure that these plates are level and their heights are equal.

First, the HLSs are installed on the plates. The liquid surface should be adjusted between the water pipe and the air pipe, and the N3 level and the DL10 spirit level are used to ensure that these HLSs are level and their heights are equal.

The installation of the WPS is more important and complicated. The process includes the installation of stretched wires and sensors. The stretched wires offer a reference for the WPS sensors. Special mechanical fixtures are designed to keep the wire stretched and stable. A 50-mm-diameter steel bar affixes the wire at the fixed end. A 150-mm-diameter fixed pulley with a V-groove holds the wire at the weight end. Each WPS sensor is installed on the three balls as mentioned above. Tiltmeters are affixed to the plates with screws (Fig. 7). At last, we use a laser tracker to measure the initial positions of all the plates when the installation is finished.

Next, we transform all plate coordinates to the MPMS coordinate system. The coordinate system of the No. 1 plate is defined as the MPMS coordinate system for this sample.

The transformation parameters from the plate coordinate systems to the MPMS coordinate system include the shift of the plates (T_x, T_y, T_z), a rotation α about the *X*-axis, a rotation β about the *Y*-axis and a rotation γ

Fig. 7 Installation of MPMS

about the Z-axis. The transformation matrix can be expressed as follows:

$$\begin{bmatrix} x_1 \\ y_1 \\ z_1 \end{bmatrix} = \begin{bmatrix} T_x \\ T_y \\ T_z \end{bmatrix} + \begin{bmatrix} \cos\beta\cos\gamma & \cos\beta\sin\gamma & -\sin\beta \\ -\cos\alpha\sin\gamma + \sin\alpha\sin\beta\cos\gamma & \cos\alpha\cos\gamma + \sin\alpha\sin\beta\sin\gamma & \sin\alpha\cos\beta \\ \sin\alpha\sin\gamma + \cos\alpha\sin\beta\cos\gamma & -\sin\alpha\cos\gamma + \cos\alpha\sin\beta\sin\gamma & \cos\alpha\cos\beta \end{bmatrix} \begin{bmatrix} x_i \\ y_i \\ z_i \end{bmatrix}. \tag{1}$$

The transformation parameters T_x, T_y, T_z, α, β, γ can be obtained from the measuring data of these sensors. The HLS and the WPS simultaneously obtain T_y. We assign the same weight to the HLS and the WPS in the vertical direction in this experiment, as mentioned in Sect. 4. The WPS sensors can obtain T_x. As mentioned below, a straight line is created to be a reference by compensating for the sag, and the relative movements of the other plates to the first plate are measured directly. T_z is a constant value measured by the laser tracker because the longitudinal alignment specifications are less critical, as mentioned in Sect. 2. The double-axis tiltmeters provide the angles α and γ. The yaw, β, can be neglected because its effect is very small. In this paper, we simplify the error propagation and ignore the error of transformation process.

A stretched wire takes the shape of a catenary because of gravity http://en.wikipedia.org/wiki/Catenary. To calculate the vertical sag of a 20-m Vectran wire, we assume that the wire describes a parabola as shown below [14].

We assume that the stretched wire is static, which means that the applied force on it must be zero. At a point D on the stretched wire, a trigonal force analysis can be obtained (Fig. 8). The model satisfies the following requirements:

1. The tension remains unchanged in the stretched wire, $\left\|\vec{T}\right\| = \left\|\vec{S}\right\| = \text{constant};$
2. The gravity g and the wire density q are also constant;
3. The vertical direction of the wire section is parallel to the Y-axis.

The coordinate system is created, and the maximum sag at point B is the zero point. The function relationship of Y and Z can be expressed as shown in Eq. (2).

$$y(z) = \frac{T}{gq}\left(\cosh\frac{gqz}{T} - 1\right) \approx \frac{gqz^2}{2T} \tag{2}$$

The horizontal distance of O and L is l. The maximum sag f is located on the $l/2$ point, which can be expressed mathematically as follows:

$$f = \frac{gql^2}{8T}. \tag{3}$$

The actual distance of every WPS sensor has been obtained by the laser tracker, as mentioned above.

The sag of the stretched wire of five WPS sensors can be calculated according to the above formula. The sag of the No. 1 WPS sensor and the No. 5 WPS are approximately zero because they are very close to the fixed end and the weight end, respectively.

The distances of the Nos. 2, 3, 4 and 5 WPSs relative to the No. 1 WPS are $L_2 = 5499.3339$, $L_3 = 10,161.4128$, $L_4 = 13,563.6214$ and $L_5 = 18,759.4679$ mm (Fig. 9), respectively.

There other parameters are $l = 18759.4679$ mm, $g = 9.7947$ m/s^{-2} and $q = 2.35 \times 10^{-4}$ kg m^{-1}. The wire is stretched by a weight of 150 N to a stress of 1 GPa. Formula 3 uses these parameters to calculate the maximum sag f.

$$f = \frac{gql^2}{8T} = \frac{9.7947 \times 2.35 \times 10^{-4} \times 18.7594679^2}{8 \times 150} = 0.675023 \text{ mm}.$$

The sag of the Nos. 2, 3 and 4 WPS can be calculated according to formula 2: $y_2 = 0.115529$, $y_3 = 0.004688$ and $y_4 = 0.134307$ mm, respectively. These sag data can be used as compensation to create a straight line.

4 Measurement and verification

After all transformation parameters have been determined, and experimental measurement is necessary to test the feasibility and reliability of the MPMS. These experiments include two parts:

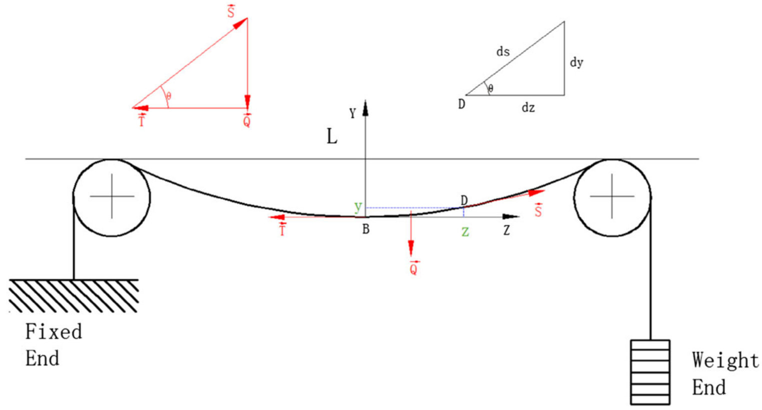

Fig. 8 *Vertical* modelling of a stretched wire

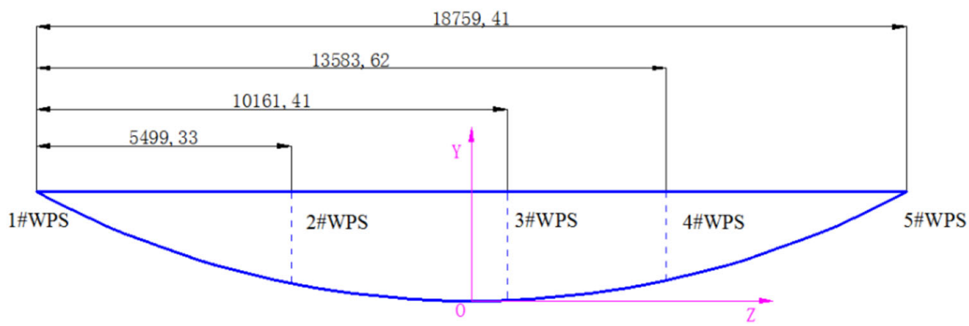

Fig. 9 Sag compensation of the stretched wires

Table 1 Coordinates of the five plates at one measuring point-in-time (mm)

Num	Axis time					
	X		*Y*		*Z*	
	Initial value	Time 1	Initial value	Time 1	Initial value	Time 1
1#	0	0.0003	0	−0.0017	0	0
2#	0	−0.0512	0	0.0154	5499.3339	5499.3339
3#	0	0.0119	0	−0.0062	10,161.4128	10,161.4128
4#	0	−0.0125	0	0.0101	13,563.6214	13,563.6214
5#	0	0.0203	0	0.0124	18,759.4679	18,759.4679

1. A comparison of the HLS and the WPS in the vertical direction verifies the accuracy of the measurement, and the tiltmeter offers a vertical compensation, as mentioned in Sect. 2.
2. Transforming the monitored data of all plates to the MPMS coordinate system.

We performed the experiment from 31 March to 2 April 2016. A temperature and humidity sensor was used to monitor the variation of the temperature and relative humidity in the experiment tunnel.

By comparing the measurement data of the HLS and the WPS in the vertical direction with the tiltmeter compensation, the differences were less than, and we assigned the same weight for the HLS and the WPS in the vertical direction.

According to the translation matrix, as mentioned above, we can obtain every plate coordinate value in the MPMS coordinate system at any measuring point-in-time (as shown in Table 1). The MPMS successfully monitored the displacement of all five plates.

5 Conclusion

This paper describes the complete design and construction process for an MPMS. In particular, the establishment and transformation process of the coordinate system from these sensors to the MPMS coordinate system is described in detail. An experimental MPMS, which included five sensors plates, was constructed in an NSRL

20-m tunnel. Some verification tests, which prove the feasibility of the MPMS, have been performed.

However, there still are some valuable issues to be researched for improving the MPMS. Comparing the effect of the temperature and humidity on the wire sag, we note that the sag is closely related to the humidity. High-precision humidity sensors have been purchased to study in depth the relationship between the wire sag and humidity. Meanwhile, the transformation method and transformation error from the MPMS coordinate system to the synchrotron source coordinate system will be studied in the next step. Overlapping stretched wires is also worth researching for expanding the MPMS measurement range, and invar is a better choice to make the plate in a practical application because of low coefficient of thermal expansion.

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