Tidal effects on hydrostatic leveling system used in high precision alignment of particle accelerator[*]

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Hydrostatic leveling system (HLS) is widely used in precision engineering survey, especially the alignment of particle accelerator, and the tidal effects on the measurement accuracy of HLS is non-ignorable, thus studies on tidal effects on the HLS is vital. A set of HLS was installed in Jingxian seismostation for verifying the methods to handle the tidal effects on the readings of HLS. Harmonic analysis of the data recorded by HLS and DSQ water tube clinometers in Jingxian seismostation and contrastive analysis of the results are completed. The tilt tide can be well reflected in the data of the both instruments and the results are both reliable. The reasons of the difference between the results are analyzed in this paper. Besides, a validation study based on the measurement data of the HLS used in SPring-8 storage ring for tidal correction on the reading of HLS is completed. The research establishes a foundation for HLS to be applied in micron-level precision alignment of particle accelerator in the future.

Keywords: Precision engineering survey, Hydrostatic leveling system, Tilt tide, DSQ water tube clinometers, Harmonic analysis

I. INTRODUCTION

A hydrostatic leveling system (HLS), based on the principle that the liquid (deionized water or purified water) in the HLS is always looking for an equipotential surface, uses connected reservoirs of water to determine elevation difference at the locations of HLS [1]. Fig. 1 briefly represents the measuring principle of HLS, among which h_1, h_2, h_3 represent the data collected from each sensor, thus the height difference Δh_1 and Δh_2 can be described as Eq. (1):

$$\Delta h_1 = h_2 - h_1,$$
$$\Delta h_2 = h_2 - h_3. \tag{1}$$

HLSs are applied in CERN (Switzerland), ESRF (France), DESY (Germany), Fermilab (USA), BEPC II (China), SLAC (USA), and SSRF (China) [2–10]. Fig. 2 shows the structural diagrams of HLS vessel used in NSRL, BEPCII and SSRF [11].
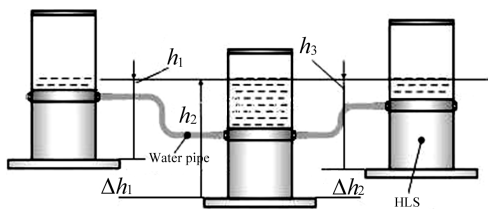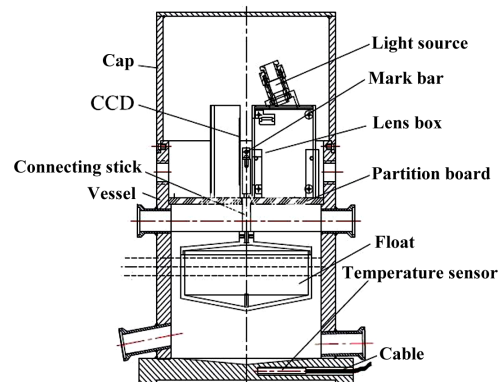

Fig. 1. Schematic diagram of HLS.

Fig. 2. Structural diagram of HLS vessel.

In precision engineering survey (micron scale), however, the tidal effects on HLS readings cannot be ignored. For instance, at CERN or SLAC, large particle accelerators were designed while taking earth tides into account for proper operation [12, 13]. Under the action of various forces, the Earth body undergoes complicated deformation. Any point on earth is affected by gravitation of the Sun and the Moon, besides the gravity and the rotational centrifugal force of the Earth. Then, the Earth deforms periodically under the action of tidal force, and this is the earth tide.

Figure 3 shows a DSQ water tube clinometer and its schematic diagram [14]. Technically, it works on the principle of liquid equipotential surface, too, but it differs from a conventional HLS in the sensors to measure the liquid level and in the structure parameters. With DSQ water tube clinometer, resolution of a hydrostatic leveling system is 0.001 arcsec and daily drift is less than 0.005 arcsec [15].
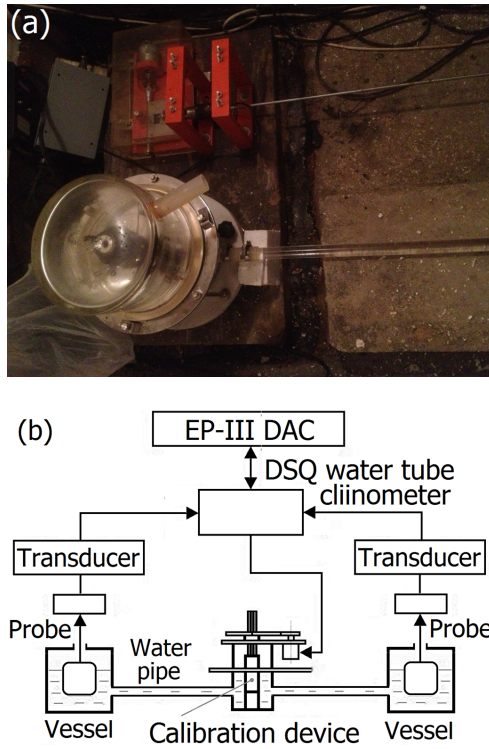
Fig. 3. (Color online) DSQ water tube clinometer (a) and its schematics (b).

DSQ system has been used in tilt tide observation in seismostation. In this paper, we report the series harmonic analysis of the data and contrastive analysis of tidal monitoring observations between HLS and DSQ, carried out at the Jingxian seismostation, Anhui, China.

II.   HARMONIC ANALYSIS OF HLS AND DSQ DATA

A.   HLS installation

A set of HLSs were installed in a cave at the Jingxian seismostation. The temperature and humidity there are stable, and the background noise is extremely low. Table 1 lists specifications of HLS installations at the seismostation.

TABLE 1. Specifications of HLS installations at Jingxian seismostation

Items	E-W segment	S-N segment
Azimuth	84.033 75°	84.033 75°
Elevation	55 m	55 m
Interval (fore and aft)	22.1 m	18.1 m
Tubing	PE	PE
Sampling interval	1200 s	1200 s

B.   Harmonic analysis of HLS data

For harmonic analysis, Fig. 4 shows the height difference of sensor readings from 10/11/2012 to 26/01/2013.
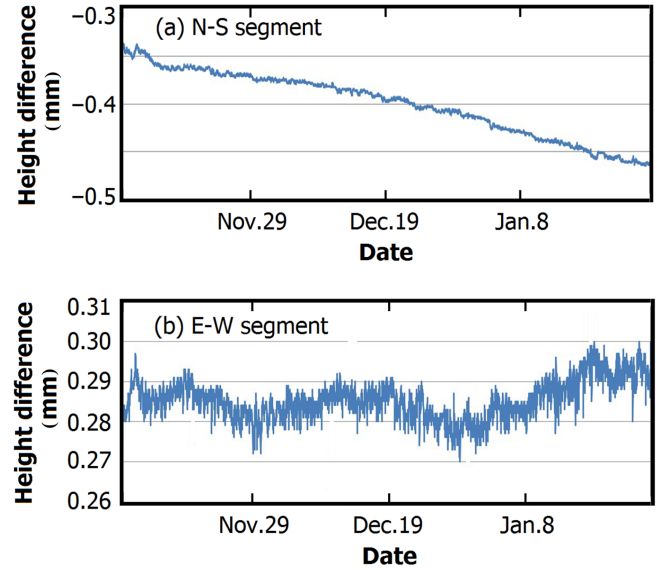

Fig. 4. (Color online) Height difference of sensor readings of the N-S (a) and E-W (b) segments.

1.   Temperature compensation

Temperature compensation shall be made to the raw data. The temperature effect on the HLS readings can be compensated by Eqs. (2)–(4):

$$\beta_{\text{water}} = -\mathrm{d}\rho/(\rho\mathrm{d}T), \tag{2}$$

$$\Delta V = (\beta_{\text{water}} - \beta_{\text{pipe}})V\Delta T, \tag{3}$$

$$\Delta h = \Delta V/S, \tag{4}$$

where, β_{water} and β_{pipe} are thermal expansion coefficient of water in the HLS vessels and the connecting pipe, respectively; T is the water temperature; ρ is the water density; ΔV is the change in water volume; ΔT is the temperature change; Δh is the height change in liquid level in the HLS vessels; and S is the internal cross-section of the vessel. Typically, $\Delta h = -0.1\,\text{mm/°C}$. The negative value is due to different thermal expansion coefficients of water (2.5×10^{-4}, 25 °C), stainless steel (4.5×10^{-5}) and PE pipe (4.5×10^{-4}), respectively.

2.   Data processing

Data handling, including linear and cubic interpolation, and multilinear regression, was done by using the T-soft
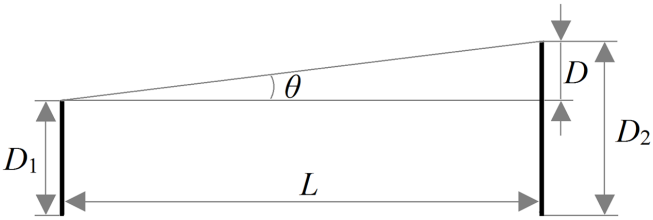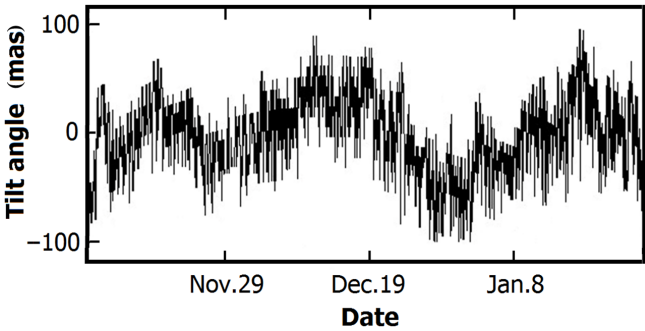
Fig. 5. Conversion diagram.

Fig. 6. Tilt angles of the E-W segment from November 2012 to January 2013, obtained using the T-soft code.

Fig. 7. Predicted tide from HLS data (N-S segment).

code recommended by ICET (International Center for Earth Tides) [16]. The tilt angle is very small (Fig. 5), so the height difference could be converted into tilt angle using Eq. (5):

$$\theta = (D_2 - D_1) \times 10^{-3} \times 3600 \times 180 \times 10^3/(L\pi), \quad (5)$$

where, D_1 and D_2 are the data (in millimeter) measured from each sensor, L is the distance between the two monitoring sites (in meter), and θ is the tilt angle (in mas, milliarcsecond). The tilt angles of the E-W segment are shown in Fig. 6 using the T-soft code.

3. Results of harmonic analysis

Harmonic analysis of HLS data was completed using the Eterna code, which is the standard software recommended by ICET [17]. The E-W and N-S tilt tidal factors of the semidiurnal and diurnal tidal waves are given in Table 2. Fig. 7 shows the predicted tide from HLS data (N-S segment) after harmonic analysis. The influence of the tidal effects is about $\pm 1\,\mu\mathrm{m}$ in $18.1\,\mathrm{m}$ by converting the tilt angle to height difference.

TABLE 2. Results of the harmonic analysis on HLS data

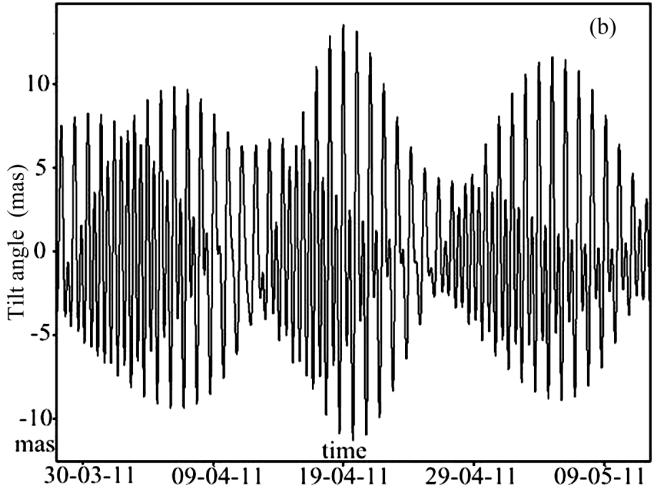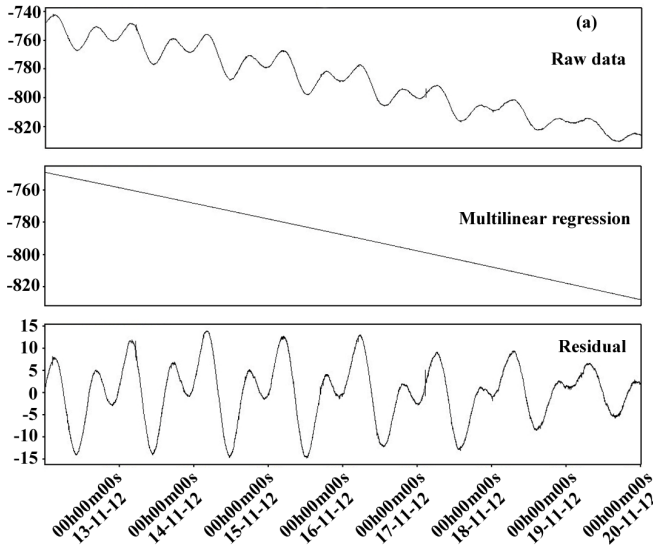| Tilt tidal factors (E-W)				Tilt tidal factors (N-S)			
Semi-diurnal		Diurnal		Semi-diurnal		Diurnal	
S_2	0.50348	Q_1	0.33916	S_2	1.06434	Q_1	0.68855
N_2	0.42331	O_1	0.41125	N_2	0.49223	O_1	0.76977
M_2	0.72582	M_1	0.4960	M_2	0.63772	M_1	0.87765
$2N_2$	0.78599	J_1	1.0380	$2N_2$	0.96087	J_1	0.59780
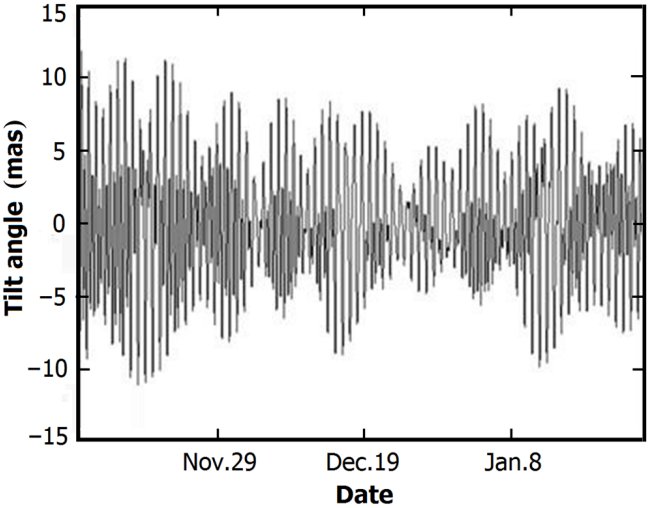
Fig. 8. Partial data before and after multilinear regression (a) and the predicted tide from DSQ data (b), for the N-S segment.

C. Harmonic analysis of data from DSQ

DSQ water tube clinometers are installed on bedrock, which is very stable. The data before and after multilinear regression are partially shown in Fig. 8(a) to reflect the tidal effects on the clinometers (in mas), with just the data of N-S segment. Fig. 8(b) shows the predicted tide from DSQ data (N-S segment) after harmonic analysis. The E-W and N-S tilt tidal factors are listed in Table 3.

TABLE 3. Result of the harmonic analysis on DSQ water tube clinometers

Tilt tidal factors(E-W)				Tilt tidal factors (N-S)			
Semi-diurnal		Diurnal		Semi-diurnal		Diurnal	
S_2	0.82839	Q_1	0.50892	S_2	0.78760	Q_1	1.03943
N_2	0.56528	J_1	0.57366	N_2	0.46880	J_1	0.91027
M_2	0.80333	J_1	0.42540	M_2	0.63136	J_1	1.01894
$2N_2$	0.58420	J_1	1.29475	$2N_2$	0.52474	J_1	1.02653

III. CONTRASTIVE ANALYSIS OF THE TILT TIDAL FACTOR

A. Damping constant of different instruments

According to Tables 2 and 3, the preliminary hypothesis is that the tilt tidal factors are related with the type of observation instruments, just as the frequency response does. And these influence factors should be investigated.

Considering the same principle of HLS and DSQ, both the instruments basically follow the Euler kinematical equation of the fluid:

$$\mathrm{d}^2D/\mathrm{d}^2t + 2\omega_0\xi_0\mathrm{d}D/\mathrm{d}t + \omega_0^2D = 0, \qquad (6)$$

where, $\omega_0 = [2sg/(SL)]^{1/2}$ is the natural angular frequency, S and s are respectively the internal cross-section of the sensor and the water tube, g is the local gravitational acceleration, and L is the distance between the two monitoring sites; and $\xi_0 = 4\pi K/(s\rho\omega_0)$ is the damping constant of the liquid surface vibration, D is the height difference between the real time height and the initial equilibrium height of the liquid surface, K and ρ are respectively the viscous coefficient and density of the liquid in the tube.

Assuming that the deviation value of the height difference in the beginning is D_0, when $t = 0$, $\mathrm{d}D/\mathrm{d}t = 0$, $D(0) = 0$, solution of Eq. (6) can be described as Eqs. (7)–(9):

$$D(t) = \frac{\xi_0 e^{-\xi_0\omega_0 t}}{\sqrt{1-\xi_0^2}}\sin\left[\sqrt{1-\xi_0^2}\,\omega_0 t \right.$$
$$\left. +\tan^{-1}\frac{\sqrt{1-\xi_0^2}}{\xi_0}\right], \quad \xi_0 < 1, \qquad (7)$$

$$D(t) = \xi_0(1+\omega_0 t)e^{-\omega_0 t}, \quad \xi_0 = 1, \qquad (8)$$

$$D(t) = \frac{\xi_0 e^{-D_0\omega_0 t}}{\sqrt{1-\xi_0^2}}\,\mathrm{sh}\left[\sqrt{\xi_0^2-1}\,\omega_0 t \right.$$
$$\left. +\mathrm{th}^{-1}\frac{\sqrt{\xi_0^2-1}}{\xi_0}\right], \quad \xi_0 > 1, \qquad (9)$$

From Eqs. (7)–(9), influence of the damping constant on movement of the liquid surface is obvious: ξ_0 is related with parameters of S, L, K, s and ρ, and basically each of the parameters of HLS differs from that of DSQ. The damping constant of HLS [1] did differ from that of DSQ [18]. Although the two instruments were installed in the same site (with the same tilt tide), the height difference $D(t)$ between the real time height and the initial equilibrium height of the liquid surface is different, hence the different calculation results of tilt tidal factors.

B. Relations between damping constant and the frequency response of the instrument

Frequency response $Q(T)$ of HLS and DSQ can be described as Eq. (10), where ξ_0 is the damping constant of the liquid surface vibration; $\alpha = T_0/T$ is the cycle ration, T_0 is duty cycle of the instrument, and T is the cycle of ground motion.

$$Q(T) = \frac{1}{\sqrt{(1-\alpha^2)^2 + 4\xi_0^2\alpha^2}}. \qquad (10)$$
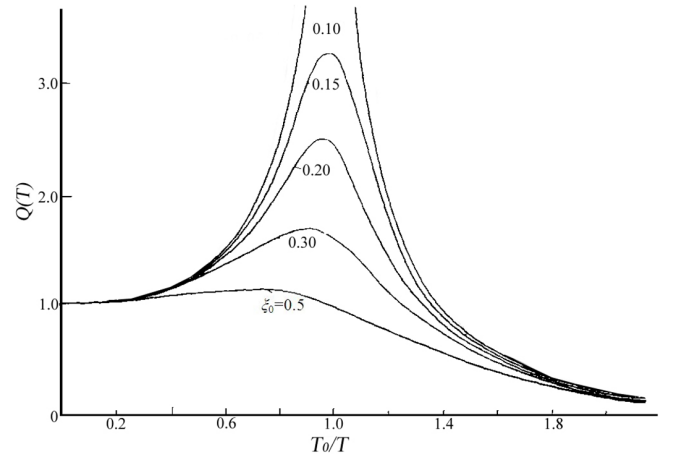

Fig. 9. Frequency response curve.

Figure 9 shows the frequency response of the instrument. According to the design parameters of HLS at Jingxian seismostation, duty cycle of the instrument is 67 s [1], which is smaller than the cycle of earth tide, the α value is almost zero, so $Q(T) = 1$ in Fig. 8(a), the tidal signal is not distorted at all. But if an earthquake or ground effect happened, sympathetic vibration would happen when the cycle of the disturbing signal is close to the duty cycle of the instrument. HLS differs from DSQ in their duty cycle and ξ_0, hence the different frequency response of the instruments. From the raw
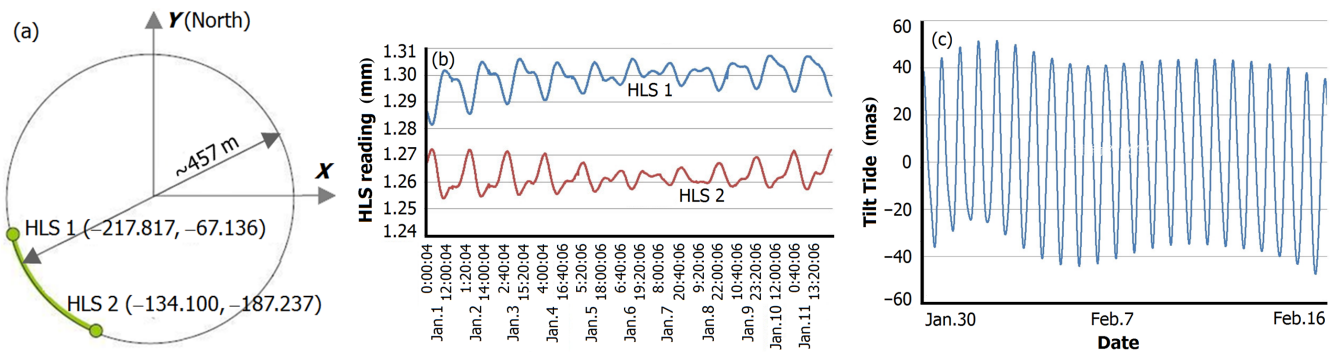
Fig. 10. (Color online) The HLS locations (a), the HLS readings (b) and the predicted tide (c) at SPring-8 in 2006.
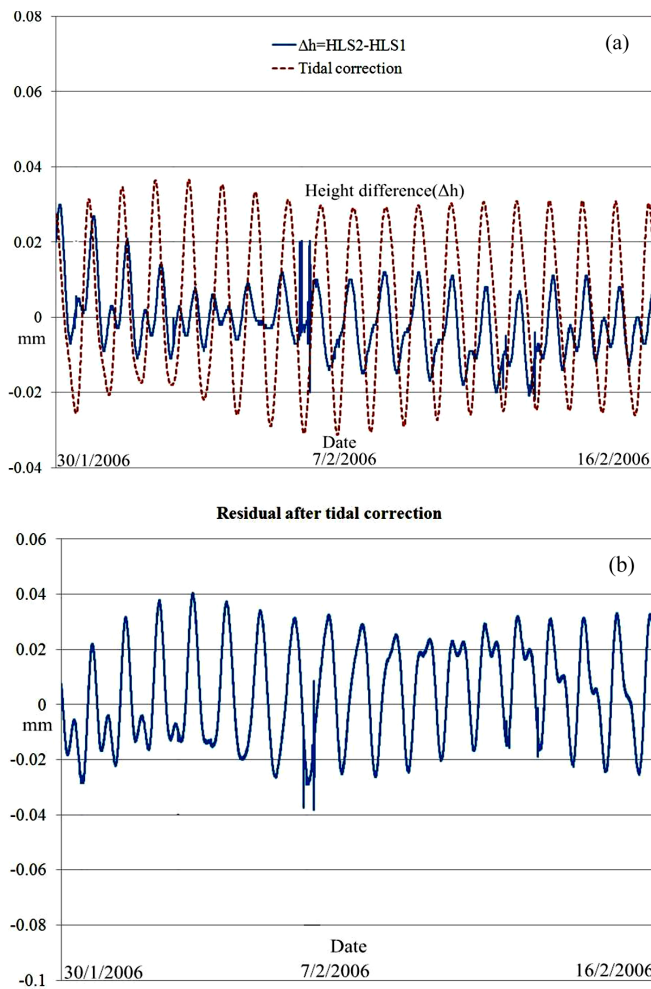

Fig. 11. (Color online) Height difference and the relative tidal correction (a), and residual signal after tidal correction (b).

data recorded by the two instruments, the sympathetic vibration phenomenon happened during the period, which might lead to different frequency domain signal distortion. This is another reason to explain the different results of harmonic analysis.

C. Results

According to the earth tide theory and Tables 2 and 3, the tilt tidal factor of M_2 is 0.68, the calculated tilt tidal factor from HLS of M_2 is 0.72582, and the value from DSQ is 0.80333. Based on the analysis above, the difference between the results of the tilt tidal factor is related with the type of observation instruments with different damping constants. In spite of a little difference between the tilt tidal factor of HLS and DSQ, but the amplitude of predicted tide of HLS data and DSQ data is the same according to Figs. 7 and 8(b). Therefore, the tilt tide can be well reflected in the data of both instruments and both the results are reliable, and the method to treat the tilt tide effects on the reading of HLS is feasible.

IV. TIDAL CORRECTION TO THE HLS DATA USED IN SPRING-8 STORAGE RING

A validation study based on measurement data of the HLS used in particle accelerator for tidal correction on the HLS reading is necessary. A set of HLSs were installed in the SPring-8 storage ring, in Hyogo, Japan, as shown in Fig. 10(a). The two HLSs, linked with pipes, were 146.4 m apart. Two HLS readings during 1/1/2006 to 11/1/2006 are shown in Fig. 10(b). The changing trend of the readings is well reflected. Through harmonic analysis to the data of HLS in SPring-8 storage ring, the local tilt tide model was calculated and predicted by the Eterna code. The results are shown in Fig. 10(c). The tidal effects on the height difference between the two HLSs are shown in dashed line in Fig. 11(a), and subtracting the residual signal after tidal correction from the height difference, the ground deformation is obtained, as shown in Fig. 11(b).

It is known that the earth tide does not affect the straightness of accelerator alignment, but it changes inclination of the whole system. So, the tidal effects on the HLS readings must be corrected, otherwise it will cause alignment errors in the particle accelerator. According to Fig. 11(a), the maximum amplitude of tilt tide model is ± 0.038 mm, in other words, the absolute influence of the tidal effects is 0.076 mm in 146.4 meters, hence the non-negligibility of the tidal effects on the

HLS readings. Due to the research on the tidal effects on HLS, related components of the accelerator are working properly, and accuracy of the alignment is improved.

V. SUMMARY

It is known that the main goal for the processing of the HLS measurements is therefore to isolate the local ground deformations from the raw measurement signal. Two different instruments to determining the ground deformations have been tried. Based on the data recorded by HLS and DSQ, and the contrastive analysis of the harmonic results, the tilt tide can be well reflected in the data of the two instruments. So the method discussed in this paper to handle the tidal effects on the readings of HLS can be proved to be feasible and reliable, the local ground deformations are obtained by deleting the tide effects on the readings of the instruments. Then the validation study based on the measurement data of the HLS used in Spring-8 storage ring for tidal correction on the reading of HLS is completed, and the maximum amplitude of the tidal effects on the readings of HLS is obtained. Obviously, the accuracy of alignment with using HLS is improved. It can be concluded that HLS application in micron-level precision alignment of particle accelerators is achievable.

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