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Abstract

The hydrostatic leveling system (HLS) is widely used in precision engineering surveying, especially for the alignment of particle accelerators, and the tidal effects on the measurement accuracy of HLS are non-negligible; thus, studies on tidal effects on HLS are vital. An HLS was installed at the Jingxian seismic station to verify methods for handling tidal effects on HLS readings. Harmonic analysis of the data recorded by HLS and DSQ water tube clinometers at the Jingxian seismic station and comparative analysis of the results were completed. The tilt tide is clearly reflected in the data from both instruments, and both results are reliable. The reasons for the difference between the results are analyzed in this paper. Furthermore, a validation study based on the measurement data of the HLS used in the SPring-8 storage ring for tidal correction of HLS readings was conducted. This research establishes a foundation for HLS to be applied in micron-level precision alignment of particle accelerators in the future.

Full Text

Tidal Effects on Hydrostatic Leveling System Used in High Precision Alignment of Particle Accelerators

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Abstract. The hydrostatic leveling system (HLS) is widely used in precision engineering surveys, particularly for the alignment of particle accelerators, where tidal effects on measurement accuracy are non-negligible. Consequently, investigating these tidal effects is essential. To verify methods for handling tidal effects on HLS readings, a set of HLS instruments was installed at the Jingxian seismostation. This paper presents harmonic analysis of data recorded by both HLS and DSQ water tube clinometers at Jingxian seismostation, along with a comparative analysis of the results.

The tilt tide is clearly reflected in data from both instruments, and both yield reliable results. This paper analyzes the reasons for differences between the results. Additionally, a validation study based on measurement data from the HLS used in the SPring-8 storage ring demonstrates tidal correction of HLS readings. This research establishes a foundation for future application of HLS in micron-level precision alignment of particle accelerators.

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

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INTRODUCTION

A hydrostatic leveling system (HLS) operates on the principle that liquid (deionized or purified water) within the system continuously seeks an equipotential surface, using connected water reservoirs to determine elevation differences at sensor locations [1]. Figure 1 [Figure 1: see original paper] illustrates the measuring principle of HLS, where h_1, h_2, and h_3 represent data collected from each sensor, allowing the height differences Δh_1 and Δh_2 to be expressed as:

$$\Delta h_1 = h_2 - h_1, \quad \Delta h_2 = h_2 - h_3.$$

HLS technology has been implemented at major accelerator facilities worldwide, including CERN (Switzerland), ESRF (France), DESY (Germany), Fermilab (USA), BEPC II (China), SLAC (USA), and SSRF (China) [2–10]. Figure 2 [Figure 2: see original paper] shows structural diagrams of HLS vessels used at NSRL, BEPCII, and SSRF [11].

In precision engineering surveys at the micron scale, tidal effects on HLS readings cannot be ignored. For instance, large particle accelerators at CERN and SLAC were designed with earth tides in mind to ensure proper operation [12, 13]. Under various forces, the Earth undergoes complex deformation. Any point on Earth' s surface experiences gravitational pull from both the Sun and Moon, in addition to Earth' s own gravity and rotational centrifugal force. Periodic deformation of the Earth under tidal forces constitutes the earth tide phenomenon.

Figure 3 [Figure 3: see original paper] shows a DSQ water tube clinometer and its schematic diagram [14]. Technically, it also operates on the liquid equipotential surface principle, but differs from conventional HLS in its liquid level sensors and structural parameters. The DSQ water tube clinometer achieves a resolution of 0.001 arcsec for hydrostatic leveling systems, with daily drift less than 0.005 arcsec [15].

This paper reports harmonic analysis and comparative tidal monitoring observations between HLS and DSQ instruments conducted at Jingxian seismostation in Anhui, China.

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1. Temperature Compensation

Temperature compensation must be applied to raw HLS data. The temperature effect on HLS readings can be compensated using the following equations:

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

$$\Delta h = \Delta V / S,$$

$$\beta_{\text{water}} = -d\rho / (\rho dT),$$

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

II. HARMONIC ANALYSIS OF HLS AND DSQ DATA

A. HLS Installation

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

TABLE 1. Specifications of HLS installations at Jingxian seismostation

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

B. Data Processing

Data handling, including linear and cubic interpolation and multilinear regression, was performed using the T-soft code recommended by ICET (International Center for Earth Tides) [16]. Since tilt angles are very small (Figure 5 [Figure 5: see original paper]), height differences can be converted to tilt angles using:

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

where D_1 and D_2 are measurements (in millimeters) from each sensor, L is the distance between monitoring sites (in meters), and θ is the tilt angle (in mas, milliarcsecond). Figure 6 [Figure 6: see original paper] shows the tilt angles of the E-W segment obtained using the T-soft code.

C. Results of Harmonic Analysis

Harmonic analysis of HLS data was completed using the Eterna code, the standard software recommended by ICET [17]. The E-W and N-S tilt tidal factors for semidiurnal and diurnal tidal waves are given in Table 2 . Figure 7 [Figure 7: see original paper] shows the predicted tide from HLS data (N-S segment) after harmonic analysis. Converting the tilt angle to height difference reveals that tidal effects influence measurements by approximately $±$1 μm over 18.1 m.

TABLE 2. Results of the harmonic analysis on HLS data

Tilt tidal factors (E-W)	Tilt tidal factors (N-S)
Diurnal	Semidiurnal
0.63772	M1

D. Harmonic Analysis of DSQ Data

DSQ water tube clinometers are installed on stable bedrock. Partial data before and after multilinear regression are shown in Figure 8(a) [Figure 8: see original paper] to illustrate tidal effects on the clinometers (in mas) for the N-S segment. Figure 8(b) [Figure 8: see original paper] 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)
Semidiurnal	Diurnal
0.82839	Q1

III. CONTRASTIVE ANALYSIS OF THE TILT TIDAL FACTOR

A. Damping Constant of Different Instruments

Comparing Tables 2 and 3 suggests that tilt tidal factors are related to the type of observation instrument, similar to frequency response characteristics. These influencing factors require investigation.

Given that both HLS and DSQ operate on the same principle, they fundamentally follow the Euler kinematical equation for fluid:

$$\frac{d^{2D}}{dt^2} + 2\omega_0\xi_0\frac{dD}{dt} + \omega_0^2 D = 0,$$

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

Assuming the initial deviation of height difference is D_0, with initial conditions $t = 0$, $dD/dt = 0$, $D(0) = 0$, the solution to Eq. (6) can be described as:

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

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

$$D(t) = \xi_0 e^{-D_0 \omega_0 t} \sqrt{1-\xi^2} \left[\sqrt{0-1}\omega_0 t + \mathrm{th}^{-1} \sqrt{\xi_0^2 - 1} \right], \quad \xi_0 > 1.$$

Equations (7)-(9) clearly show that the damping constant significantly influences liquid surface motion: ξ_0 depends on parameters S, L, K, s, and ρ, which differ between HLS and DSQ instruments. The damping constant of HLS [1] indeed differs from that of DSQ [18]. Although both instruments were installed at the same site (experiencing the same tilt tide), the height difference $D(t)$ between real-time height and initial equilibrium height differs, leading to different calculated tilt tidal factors.

B. Relations Between Damping Constant and Frequency Response

The frequency response $Q(T)$ of HLS and DSQ can be described as:

$$Q(T) = \sqrt{(1-\alpha^2)^2 + 4\xi^2},$$

where ξ_0 is the damping constant of liquid surface vibration; $\alpha = T_0/T$ is the cycle ratio, T_0 is the instrument' s duty cycle, and T is the cycle of ground motion.

Figure 9 [Figure 9: see original paper] shows the instrument's frequency response curve. According to design parameters for HLS at Jingxian seismostation, the instrument' s duty cycle is 67 s [1], which is smaller than the earth tide cycle, making the α value nearly zero and $Q(T) \approx 1$ in Figure 8(a). Thus, the tidal signal experiences no distortion. However, if an earthquake or ground effect occurs, sympathetic vibration arises when the disturbing signal' s cycle approaches the instrument' s duty cycle.

HLS and DSQ differ in duty cycle and ξ_0, resulting in different frequency responses. Raw data from both instruments show sympathetic vibration phenomena during the observation period, which may cause different frequency domain signal distortions. This provides another explanation for the different harmonic analysis results.

C. Results

According to earth tide theory and Tables 2 and 3, the theoretical tilt tidal factor of M2 is 0.68, while the calculated value from HLS is 0.72582 and from DSQ is 0.80333. Based on the above analysis, differences in tilt tidal factors relate to instrument types with different damping constants.

Despite minor differences between HLS and DSQ tilt tidal factors, the amplitude of predicted tides from both datasets is identical, as shown in Figures 7 and 8(b). Therefore, the tilt tide is well reflected in both instruments' data, both results are reliable, and the method for treating tidal effects on HLS readings is feasible.

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

A validation study using measurement data from HLS installed in a particle accelerator is necessary for tidal correction of HLS readings. A set of HLS instruments was installed in the SPring-8 storage ring in Hyogo, Japan, as shown in Figure 10(a) [Figure 10: see original paper]. Two HLS units connected by pipes were spaced 146.4 m apart. Figure 10(b) [Figure 10: see original paper] shows readings from both HLS units during January 1–11, 2006, clearly reflecting the changing trend.

Harmonic analysis of SPring-8 HLS data using the Eterna code calculated the local tilt tide model, with results shown in Figure 10(c) [Figure 10: see original paper]. Tidal effects on height difference between the two HLS units appear as a dashed line in Figure 11(a) [Figure 11: see original paper]; subtracting the residual signal after tidal correction from the height difference yields ground deformation, shown in Figure 11(b) [Figure 11: see original paper].

Earth tide does not affect accelerator alignment straightness but changes the entire system' s inclination. Therefore, tidal effects on HLS readings must be corrected to prevent alignment errors. According to Figure 11(a), the maximum amplitude of the tilt tide model is \$±\$0.038 mm, meaning the absolute tidal influence is 0.076 mm over 146.4 meters—demonstrating the non-negligibility of tidal effects on HLS readings. Research on these tidal effects has enabled proper operation of accelerator components and improved alignment accuracy.

V. SUMMARY

The primary goal of HLS measurement processing is to isolate local ground deformations from raw measurement signals. Two different instruments for determining ground deformations were evaluated. Based on data recorded by HLS and DSQ, and comparative analysis of harmonic results, the tilt tide is well reflected in both instruments' data. The method discussed herein for handling tidal effects on HLS readings proves feasible and reliable, allowing local ground deformations to be obtained by removing tidal effects from instrument readings.

The validation study using SPring-8 storage ring HLS measurement data completed tidal correction analysis, yielding the maximum amplitude of tidal effects on HLS readings. Clearly, alignment accuracy using HLS improves with this correction. It can be concluded that HLS application in micron-level precision alignment of particle accelerators is achievable.

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Note: Figure translations are in progress. See original paper for figures.