

Applying ultrasonic echolocation-based measurement method to increase the accuracy of leveling instruments

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Abstract

Current mechanical, laser and electronic leveling instruments are sometimes not accurate enough to be used for determining either vertical or horizontal level for level-critical applications. By using an ultrasonic echolocation-based distance meter it is possible to design very accurate leveling instruments for a wide range of applications. This article overviews the accuracy of current leveling instruments and compares it with the achievable accuracy of the proposed leveling devices. Level determination of horizontal and vertical surfaces using mechanical devices is explained. By combining the ultrasonic distance determination method with the mechanical level determination methods, very precise leveling instruments can potentially be created. Some exemplary designs of such leveling instruments are presented. In addition, basic operating principles of an ultrasonic echolocation-based distance measurement device are presented, along with sources of measurement errors of such devices. Solutions for eliminating measurement errors are discussed. Since accuracy is the top priority, we suggest creating an isolated operating environment for acoustic measurements. A practical example of using a leveling device with implemented ultrasonic measurement method is presented along with measurement results.

Keywords: leveling instruments, mechanical levels, vertical level, horizontal level, accuracy of leveling instruments, plumb-bob, plumb-line declination, ultrasonic echolocation-based meter, ultrasonic distance measurement, measurement accuracy, measurement environment, spirit-level

Introduction

For vertical (vertical surface) and horizontal (horizontal surface) determination in practice, various mechanical, electronic, and laser leveling instruments are used [1-5]. The measurement uncertainty of current mechanical levels is up to 0.5 mm/m. Electronic and laser levels have measurement uncertainty up to 0.2 mm/m.

The accuracy of such leveling instruments depends on the quality of production and the determination of a bubble or plumb-bob position [5]. When using a plumb-bob, the determination of vertical surface depends on the alignment of the plumb-line to the surface of the measurement bar. In this case, the accuracy depends on the length of the plumb-line, when the plumb-line declination from the vertical surface is constant.

The horizontal surface is determined either by the position of the air bubble in the measurement vessel or by using a liquid-filled tube and measuring the level of the liquid inside [2-5]. In this case, accuracy depends on the length of the tube, i.e., is also proportional to the length of a measurement base.

In both cases, a position has to be measured of either the plumb-line, which is always pointed towards the gravitational center of the Earth; or the surface of liquid, which has a plane perpendicular to the direction of gravity of the Earth. These position measurements are either visual or measured by using electronic or laser devices.

As mentioned [1], the measurement uncertainty of laser and electronic levels is about 0.2 mm/m. Sometimes in practice, when adjusting the level in special construction work challenges, or for level-critical equipment, a significantly larger level accuracy is required.

We propose to use an ultrasonic echolocation-based distance measurement method to measure the position of a plumb-line, and the distance to the surface plane of the liquid, with respect to constructional elements of the leveling instrument.

When measuring distances in air with an ultrasonic echolocation-based level meter, measurement error no larger than ± 0.005 mm is achieved [6-9]. The dimensions of the electro-acoustic measurement system are relatively small (the volume of the transducer is no larger than 1 cm³). As will be presented below, such properties of the measurement system are suitable to apply ultrasound for leveling instrument designs.

Overview of measurement error sources

Acoustic (ultrasonic) echolocation-based meters are widely applied for various distance measurements [8-13]. The operating principle of such meters is based on measuring the duration of measurement signal's propagation to the object and back. Many of such meters use pulse measurement signals.

Varying operating environment, in which ultrasonic distance meters operate, is a source of a range of measurement errors.

When measuring in a range of temperatures, measurement errors, which occur due to the dependence of acoustic measurement signal's velocity on temperature, need to be determined and compensated [6].

The error of measured distance in this case is determined by the changes of ultrasound velocity due to variations in the temperature of the environment (~ 0.17 % for a change of one degree in temperature). This measurement error can be compensated by applying

parametric thermo-compensation [6], which reduces this measurement error down to 0.01 % for a change of one degree in temperature.

The accuracy of measurement also depends on the design of the electro-acoustic system. The measurement error mostly depends on the thermal expansion of the constructive elements and on parasitic signal propagation through constructive elements from transmitter directly to receiver, instead of the signal's required path through air to the surface of measurement object and back [6].

To avoid the influence of the environment on measurement results, we later suggest constructing a measurement chamber, thus separating the environment of the measurement signal's path from the environment around the measurement device.

When analyzing the influence of a particular echolocation-based meter on a measurement accuracy, choice of a measurement system (layout) is important. The measurement system can be with two electro-acoustic transducers (Fig. 1), one of which transmits and the other receives the measurement signals [6].

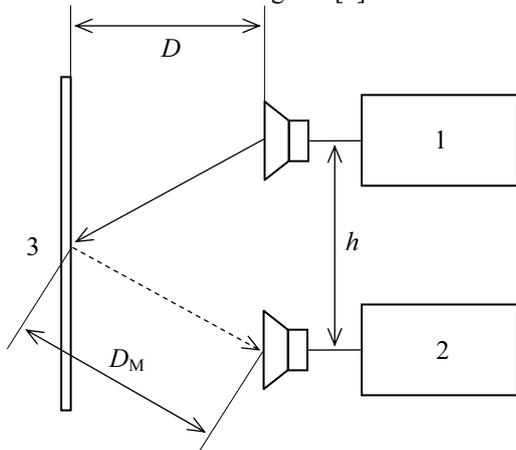


Fig. 1. Measurement system with two electro-acoustic sensors: 1 – transmission block of measurement signals; 2 – reception and processing block; 3 – measurement object

The other option is to use a single transducer that transmits and receives measurement signals.

When the distance D_M (Fig. 1) changes in the process of measurement, the distance to the object D is calculated by the measurement system using expression [6]:

$$D = \sqrt{D_M^2 - \left(\frac{h}{2}\right)^2}. \quad (1)$$

Using Eq. 1, the actual distance D is calculated based on the distance D_M . One can see from Eq. 1 that by decreasing the distance h , the systematic measurement error also decreases. For example, if $h = 10$ mm and the measured distance changes by 1 mm, the measurement error is 0.11 mm. Therefore, the distance h should be as minimal as possible.

In a measurement system option with one transducer, the distance h is zero and such measurement error is no longer present.

Other source of measurement errors is from the chosen electronic measurement structure, in which the measured propagation time errors of the measurement signal occur due to insufficient signal-to-noise ratio [14-16].

Additionally, measurement errors are caused by various electronic signal delays in electronic circuits [17-18].

An additional measurement channel of the meter can be used as a calibrated channel for determining the exact velocity of sound when the operating environment is unstable [19-23]. The transducer frequency is in 0.8... 2 MHz range. The transmitters are excited by one half-period electric pulse. The detection circuit for determining zero crossing is used in the receiving channel of measurement signals. This way, the obtained measurement accuracy is the same as of the phase method [7]. The obtained time interval, proportional to the measured distance, is filled by 100 MHz marks. A counter counts these marks, which are later processed by a processor. The processor performs the primary processing of measurement information (eliminating the changes of ultrasound velocity, calculating average results, etc.).

When trying to reach the minimal distance measurement error, an additional standard calibrated measurement channel has to be implemented. The measurement channel needs to be shielded from negative environmental factors by constructing a measurement chamber with a stable environment. In practical echolocation-based short distance meters in the measurement interval of 10... 30 mm, the measurement error is ± 0.005 mm [6].

Level determination methods

One of our proposed applications of the ultrasonic distance measurement for a vertical leveling instrument design is schematically presented in Fig. 2.

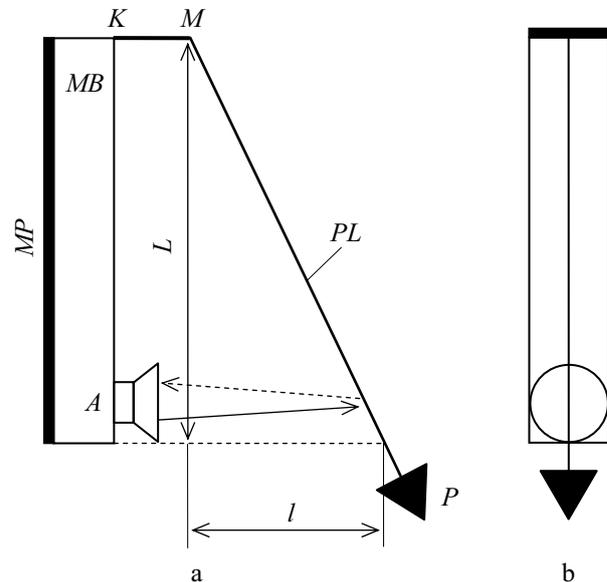


Fig. 2. Schematic diagram of a leveling instrument for vertical surface determination

A small beam KM is fitted on the top of the measurement bar MB (Fig. 2). On the end of this beam, a plumb-bob P is attached with a line. The plumb-bob always points towards the gravitational center of the Earth. On the bottom of the measurement bar an antenna of the ultrasonic echolocation-based level meter is mounted. The antenna is directed at the plumb-line PL .

The measurement bar is placed against the object with its measurement plane MP . The verticality of the measurement bar in a perpendicular plane (Fig. 2b) is determined visually by a maximally reflected acoustic signal from the plumb-line. The distance from the measurement bar to the plumb-line is measured using the ultrasonic distance meter. The longer the distance l (which can be either positive or negative), the greater is the declination of the measurement plane from the vertical plane.

The accuracy of the leveling instrument is proportional to the distance L .

When the measurement error of the ultrasonic distance meter is ± 0.005 mm and the measurement bar is two meters long, the measurement error of the leveling instrument is about 0.003 mm/m.

It needs to be noted, that practical measurements will be influenced by the unstable environmental conditions mentioned above. Therefore, an additional protective cylinder should encase the antenna and plumb-line. This would significantly decrease the influence of turbulence on the accuracy of measurement results. When such leveling instrument is used for long-term measurements, it has to be periodically recalibrated or an additional calibrated measurement channel has to be implemented. This channel would eliminate the influence of varying environmental parameters on measurement results.

A schematic diagram for a horizontal table is presented in Fig. 3.

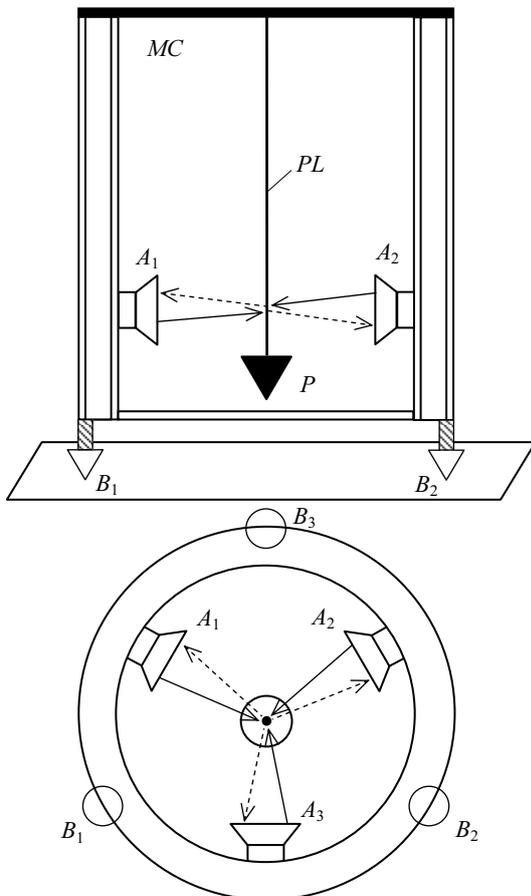


Fig.3. Schematic diagram of a table with precise horizontal surface adjustment (side and top views)

The table has a sealed round measurement chamber MC with a stable, non-turbulent environment to eliminate the negative effects of the surrounding environment on a measurement accuracy. Antennas A_1, A_2, A_3 are mounted on the inner wall near the bottom of the chamber, separated by 120° . The antennas are pointed towards the center of the chamber. On the chamber's ceiling in the center, a plumb-bob P is attached with a plumb-line PL . The plumb-bob always points towards the gravitational center of the Earth. The table has three adjustable legs mounted on the outer wall of the table, separated by 120° .

The table legs B_1, B_2, B_3 are adjusted until the signal propagation time for each antenna becomes equal. At this point, the surface of the table is horizontal.

Such precise leveling instruments are needed to determine the level for level-critical systems.

For example, in Kruonis hydro-accumulative power station, Lithuania, turbine shaft declination was measured against a vertical plane in regard with respect to the upper reservoir (UR), lower reservoir (LR), left shore (LS) and right shore (RS). The declination was measured using a two-channel ultrasonic echolocation-based distance meter, using a 32 MHz pulse mark frequency. Measurements were made along the shaft axis with a measurement base of 2 meters, with respect to the vertical plane. The measurement results are presented in Fig. 4. In Fig. 4, four-digit numbers show the 32 MHz mark pulse difference, counted between two measurement channels, which were placed on the top and on the bottom of the shaft.

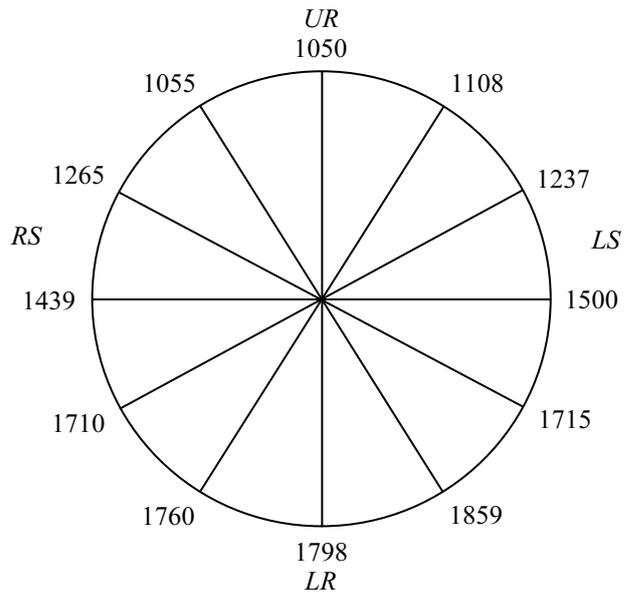


Fig.4. Experimental measurement results of turbine shaft declination against a vertical plane. The point-of-view is towards the upper reservoir. The highest four-digit number indicates the direction of declination

The horizontality of the shaft's end plane could be determined by measuring the declination of the end plane against a horizontal surface in 3 different points. A schematic diagram for such device is presented in (Fig. 5).

In Fig. 5, a schematic diagram of a leveling instrument for horizontal surface determination is presented. Antennas A_1, A_2, A_3 of the ultrasonic distance meter are arranged in a shape of an equilateral triangle over the measurement

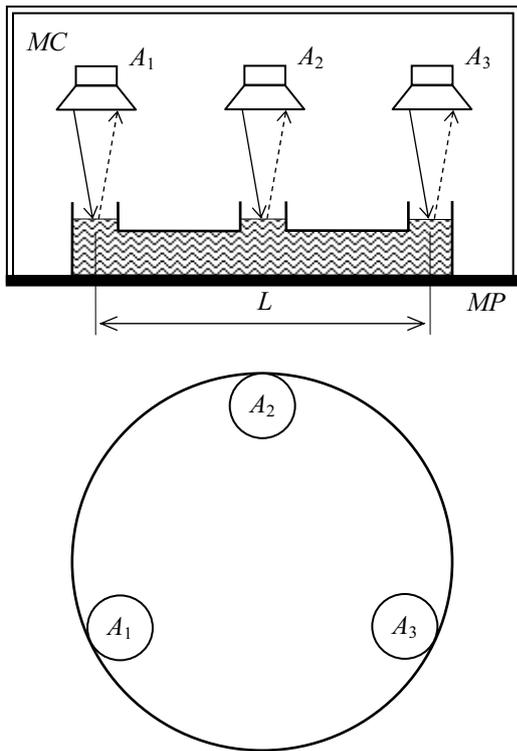


Fig. 5. Schematic diagram of a leveling instrument for horizontal surface determination (side and top views)

vessel, which is filled with liquid. In this case, the accuracy of the leveling instrument is proportional to the distance L . The determination of a horizontal surface with ultrasonic distance meter is simple, as it is sufficient to orient the instrument in such a way, until the signal propagation time for each antenna becomes equal.

It is also possible to implement the ultrasonic distance measurement method in standard spirit-level designs (Fig. 6).

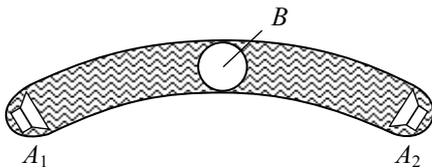


Fig. 6. Schematic diagram of a spirit-level with implemented ultrasonic distance measurement method

Antennas A_1 and A_2 are mounted in the ends of a curved tube, which is filled with liquid and has an air bubble B . The air bubble is always inline with a gravitational pull of the Earth. The spirit level is horizontal when the air bubble is located at the center of the tube.

Measurement signals from antennas A_1 and A_2 are reflected from the air bubble. When the signal propagation times become equal, the spirit-level is horizontal.

This ultrasonic level determination can complement the visual level determination, for example, by producing an audible beep, when level is achieved.

Conclusions

By using an ultrasonic echolocation-based distance meter it is possible to design very accurate leveling instruments for a wide range of applications.

The implementation of the ultrasonic echolocation-based distance measurement method for level determination is based on measuring the declination of a plumb-line, or the distance to the surface plane of the liquid, in with respect to constructional elements of the leveling instrument.

A sealed measurement chamber eliminates the negative effects of a turbulent environment thus increasing the accuracy of measurement.

By combining the ultrasonic distance determination method with mechanical level determination methods, very precise leveling instruments can potentially be created.

Due to their high accuracy such leveling devices can be used to determine either horizontal or vertical level for level-critical applications.

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Ultragarsinio aidolokacinio metodo taikymas vertikalės ir horizontalės nustatymo tikslumui padidinti

Reziumė

Matuojant atstumus ore ultragarsiniu aidolokaciniu metodu, palyginti nesunkiai galima pasiekti, kad matavimo paklaida būtų ne didesnė kaip $\pm 0,005$ mm. Elektroakustinės matavimo sistemos geometriniai matmenys yra santykinai nedideli (keitiklio tūris neviršija 1 cm^3). Išvardytos ypatybės įgalina taikyti ultragarsą gulsčių technikoje.

Vertikalei (vertikaliai plokštumai) ir horizontalei (horizontaliai plokštumai) nustatyti praktikoje plačiai naudojami įvairių konstrukcijų mechaniniai, elektroniniai ir lazeriniai gulsčiai. Šiuolaikinių mechaninių gulsčių tikslumas yra iki $0,5 \text{ mm/m}$, o elektroninių ir lazerinių – $0,2 \text{ mm/m}$.

Siūloma gulsčių tikslumą padidinti ultragarsiniu aidolokaciniu metodu. Jis pagrįstas horizontaliosios gulsčių plokštumos nuokrypio nuo skysčio paviršiaus atstumo matavimu trijuose taškuose. Matuojant vertikale, siūloma atstumą iki svambalo lyno matuoti trijuose horizontaliosios plokštumos taškuose. Nustatant vertikalią plokštumą, siūloma matuoti svambalo lyno nuokrypį viename taške, o statmenoje plokštumoje svambalo nuokrypį pakanka nustatyti vizualiai. Siūlomo metodo tikslumas priklauso nuo pasirinktos matavimo bazės atstumo. Pvz., kai matavimo bazė 2 m , nustatymo paklaida yra $\pm 0,003 \text{ mm/m}$.

Aptariamasis metodas gali būti naudingas ten, kur reikia specialaus techninio preciziškumo, pvz., nustatant turbinų velenų precizinį vertikalumą ir horizontalumą, taip pat justuojant lazerinius teodolitus ir kitur.

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