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Automated measuring devices for pendulum wire displacements

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Abstract: The article describes the construction and principle of operation of two prototype devices: a laser device and an inductive device for measuring the pendulum wire displacement. A rotating laser beam and two inside detectors (fixed), as well as two external detectors were used in the first device. Falling on the detectors, the laser beam will cause them to generate electrical signals. The time differences between the signals generated by the internal (fixed) and external detectors are a function of the pendulum wire displacement. Inductive sensors mounted inside the measuring head, which is fixed to a cross-truck, moving along the perpendicular *X* and *Y* axes in the range of 50 mm, were used in the second device. The cross-truck is moved by stepper motors, and the inductive sensors placed in the *X* and *Y* axes search for the location of the pendulum wire. The number of steps of the stepper motors is a measure of the pendulum wire displacement along the *X* and *Y* axes.
Such devices are used to control the deviation of verticality of tall hydro-technical facilities mainly due to the action of internal stresses and external factors such as temperature and the water level in the tank.

Keywords: deviation of verticality, measurement of displacement, pendulum, pendulum wire, hydro-technical facilities

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1. Introduction

Tall structures are deviated from verticality mainly due to the action of internal stresses and external factors (Brys, 2000). On account of the safety of such structures, in particular hydro-technical ones, it is necessary to systematically monitor and measure deformations in accordance with a schedule of measurements (Brys, 2000; Janusz and Janusz, 2004). Inclinometers and pendulums are used for measuring inclinations of structures. A pendulum consists of a wire mounted at the highest possible point of a structure and a weight submerged in a tank with oil, and fixed at the lowest possible point of this structure. Placing the weight in the oil tank serves the purpose of damping the pendulum wire vibrations, thus increasing the accuracy of measurement. Inverse pendulums, in which the wire is mounted at the lower part of a structure, with the oil tank and the float fixed high in the upper part, are also used. Measurements of the pendulum wire displacement are performed manually, or in automated measurement systems, and consist in measuring changes to the position of the wire against a set of reference planes.

In many structures, due to difficult environmental conditions, measurements of pendulum wire displacements are performed only using manual opto-mechanical instruments (Janusz et al., 1974). Such measurements are time-consuming and, therefore, are performed not more than a few times a year. There are also structures on which automated measuring systems recording changes in various parameters affecting the security of a structure are installed; such systems in many cases do not, however, record changes to the position of the pendulum wire (Smolka, 1994).

It was in the Institute of Geodesy and Cartography, in cooperation with OLBRYSZ ELECTRONIC company, that prototypes of devices for measuring the pendulum wire displacement, which can be used on almost all tall hydro-technical structures, were developed and constructed. These devices can be installed on tested structures and connected to the automated systems of measuring displacements and deformations functioning there, without interrupting the continuity of measurements carried out using manual instruments. Due to the severe conditions in which a device measuring the pendulum wire displacement operates, the development of such a device is a very difficult matter.

However, efforts have been made to develop the construction of such a device. The results of this work include prototypes, publications (Mirek, 2003) and patents (Cmielewski, 2003; Ohtomo Fumio, 2003; Bryś and Cmielewski, 2004; Kolodziejczyk and Olbrysz, 2007).

2. Description of the devices

The first device implementing the measurement of pendulum wire displacements, designed and constructed at the Institute of Geodesy and Cartography, is a laser device (Kolodziejczyk and Olbrysz, 2007). The principle of operation of this device is presented in Figure 1. This device consists of a laser light source, a rotating mirror, two tag detectors and two receiving detectors. These elements are enclosed in a shared sealed housing, which is partly opened for the time of conducting measurements, and then closed after their completion. The beam emitted by the laser light source is reflected from the rotating mirror, creating a rotating beam which, falling on the tag detectors, causes them to generate electrical impulses. At the same time, the beam reflected from the pendulum wire falls onto the receiving detectors, which also induce electrical impulses. The time differences in the reception of the electrical impulses generated by the tag detectors and receiving detectors are a function of the angular displacement of the pendulum wire. The device must be mounted on a structure in such a way that the pendulum wire is located between two straight lines intersecting at the axis of rotation of the reflecting element (mirror), and passing through the first and the second tag detector. Owing to the use of a rotating laser beam, the device allows the continuous measurement of changes to the inclination of a structure relative to the pendulum wire, while the use of an electronic system enables remote, reliable, and above all, precise measurement of these changes. Pendulums controlled by devices with the remote measurement of deviations can be connected to automated control systems of hydro-technical structures.

In the described device, there is no need to define the angle of the emitted laser beam relative to the horizontal, or the angular positioning of the detectors.

In the presented solution, two devices with a rotating laser beam (Fig. 2) are installed at a right angle to determine the pendulum wire displacements in the perpendicular axes *X* and *Y*. The devices can be adjusted along both *X* and *Y* axes which have been oriented accordingly to the orientation of *X* and *Y* axes of coordinate system established on the object for manual measurements.

Taking into account the specificity of different hydro-technical structures and conditions in which they operate, an inductive device was designed, with which measurements of the pendulum wire displacements in conditions of high dustiness and

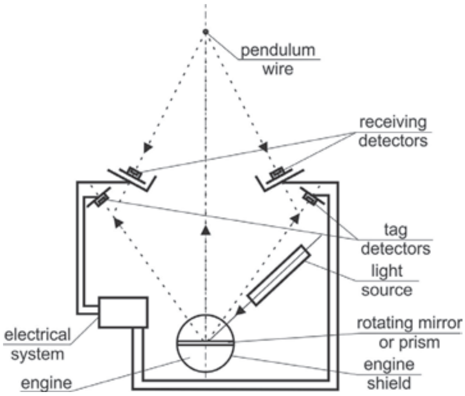

Fig. 1. A diagram of a laser device for measuring pendulum wire displacements

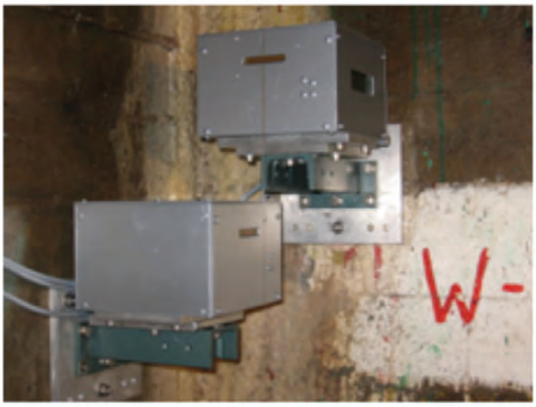

Fig. 2. Laser devices mounted on a structure

humidity can be performed. Inductive sensors which allow non-contact measuring, searching for the wire, and registering changes to the position of the pendulum wire, were used in this device. Inductive sensors are characterized by trouble-free operation and high resistance to harsh outdoor conditions.

Figure 3 shows examples of operating conditions of devices for measuring the pendulum wire displacements. As can be observed, the operating conditions of automated devices measuring changes to the pendulum wire position are very difficult; they are also difficult to handle by persons performing these measurements manually.

Fig. 3. A measuring position of pendulum wire displacements using a mechanical device

This device consists of a cross-truck and a truck-mounted measuring head with five inductive sensors (Fig. 4). The cross-truck is fixed to a support plate and the whole is encased in a housing, from which the measuring head with inductive sensors juts out. The cross-truck is moved by screws with a pitch of 2 mm, which are rotated by stepper motors with a frequency of 200 steps per revolution. This allows measuring the pendulum wire displacement in the *X* and *Y* axes with an accuracy of 0.01 mm. In practice, it is estimated that the measurement accuracy of the device should be not less than 0.05 mm with the measuring range of 40 mm.

The measuring head shown in Figure 4 is equipped with five inductive sensors. The coarse sensor is designed to search for the initial pendulum wire position and may be fixed along the *X* or *Y* axes. In the figure, the sensor is mounted along the *Y* axis. After mounting the device on a structure and connecting it to the electronic systems, the device proceeds to search for the position of the pendulum wire. To accomplish this, the head, together with the table, moves along the *X* axis in the entire measuring range, and if the coarse sensor does not register the wire position, the cross-truck with the head moves along the *Y* axis within the measuring range of the coarse sensor, and the return shift of the head along the *X* axis follows. These activities are carried out until the coarse sensor detects the position of the pendulum wire. Following the location of the wire position by the coarse sensor, a shift of the cross-trucks along the *X* and *Y* axes occurs so that the wire is recorded by the two sensors mounted along the *X* axis, and the two sensors mounted along the *Y* axis. Such a shift is possible because the distances between the coarse sensor and the sensors mounted along the *X* and *Y* axes are known structurally. This shift is implemented by a measuring programme controlling the operation of the stepper motors. From this point, when the wire moves relative to the sensors mounted along the *X* and *Y* axes, the logical statuses at their output will change, and the stepping motors guiding the measuring head with the sensors mounted along the *X* axis and *Y* axis will be activated so that the pendulum wire reaches the position at the intersection of the planes passing through the sensors of the *X* and *Y* axes. In order to determine the direction of the pendulum wire displacement, the fronts of the sensors placed along the *X* and *Y* axes are shifted

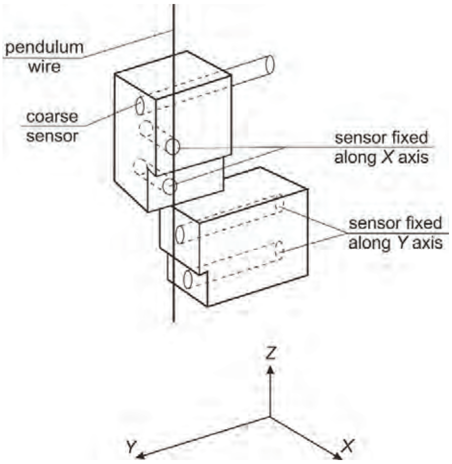

Fig. 4. A diagram of the measuring head

relative to each other. If the X axis or Y axis sensors do not send electrical impulses, it means that the wire is moved away from these sensors, and the control systems will run the motors and cause the automatic alignment of the tables with the head by as much as is necessary to have the signal from only one sensor mounted along the X and Y axes. However, when signals are received from both of the sensors mounted at the X or Y axes, the tables and the head will be moved away, since it means that the pendulum wire is too close to the inductive sensors. Truck sliding tables have predetermined fixed zero positions against which the magnitude of the displacement will be determined. The magnitude of the pendulum wire displacement along the X and Y axes will be measured based on counting the steps made by the stepper motors sliding the tables, and thus by the measuring head along the X and Y axes.

The cross truck table, stepper motors, and the measuring head (on the left in the figure) of the inductive device for measuring the pendulum wire displacement are shown in Figure 5.

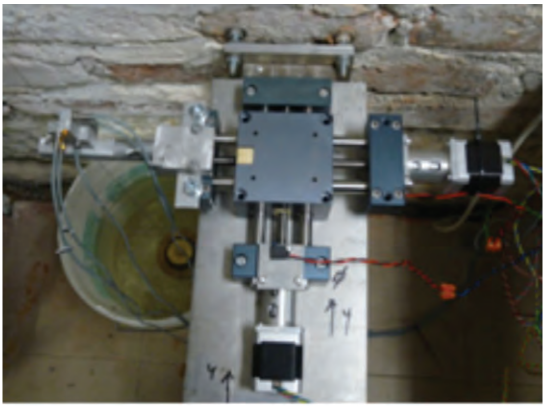

Fig. 5. The inductive device without its housing at a test stand

The use of such instruments for measuring tall buildings, especially hydro-technical structures, will allow a more accurate and easier analysis of their behaviour, and the evaluation of their safety.

3. Trial tests

Test stands, on which shifts in the X and Y axes within the range of up to 25 mm and with an accuracy of 0.01 mm can be made, were designed and constructed for the laboratory testing of devices designed to measure pendulum wire displacements.

The results of laboratory tests of the device with a rotating laser beam are shown in Table 1, where X_s and Y_s are the reference displacements, respectively along the X and Y axes, whereas X_p and Y_p are the readings of the device for the displacements along the X and Y axes, respectively.

The differences $X_s–X_p$ and $Y_p–Y_p$ between the reference displacements and the readings of the device in the X and Y axes respectively (Table 1) do not exceed 0.02 mm. It also follows from the data presented in Table 1 that the measuring accuracy of the device obtained during the tests should be confirmed in the course of the pendulum wire displacement measurements in the field, at a hydro-technical facility.

Table 1. The results of measuring structure deformations [mm]

No	X_{man}	X_{las}	$X_{man}(n–1)$	$X_{las}(n–1)$
1	8.73	0.29	–0.11	–0.09
2	8.62	0.20	–1.24	–1.18
3	7.38	–0.98	–0.10	–0.06
4	7.28	–1.04	–0.03	0.01
5	7.25	–1.03	0.00	0.04
6	7.25	–0.99		

On account of the optical systems used in this solution, the device may be used at structures with average dustiness and humidity. As part of the tests performed, the prototype was mounted and tested at a hydro-technical structure, where the results of the X_{las} values of the pendulum wire displacement measured with the device practically did not differ from the X_{man} results of measurements made using a manual instrument (Table 2).

Table 1 shows the results of measuring structure deformations which occurred within a period of two months. The maximum difference of readings of the manual and laser instruments was 0.06 mm, and is within the measurement error of the manual instrument.

The results of measurements taken using the manual device are the mean values of several measurements taken.

Table 2. Results of laboratory tests of the device with a rotating laser beam [mm]

No	X_s	Y_s	X_p	Y_p	$X_s - X_p$	$Y_s - Y_p$
1	0.000	0.000	–0.004	–0.006	*0.004*	*0.006*
2	0.000	5.000	–0.002	4.998	*0.002*	*0.002*
3	5.000	5.000	5.015	5.018	*–0.015*	*–0.018*
4	–5.000	5.000	–4.993	4.988	*–0.007*	*0.012*
5	–5.000	10.000	–4.992	9.994	*–0.008*	*0.006*
6	–10.000	5.000	–10.003	4.983	*0.003*	*0.017*
7	–10.000	0.000	–9.993	–0.001	*–0.007*	*0.001*
8	–10.000	–5.000	–10.015	–5.002	*0.015*	*0.002*
9	–10.000	–10.000	–9.997	–10.001	*–0.003*	*0.001*
10	0.000	–10.000	–0.010	–10.009	*0.010*	*0.009*
11	5.000	–10.000	5.008	–10.011	*–0.008*	*0.011*
12	10.000	–10.000	9.984	–9.994	*0.016*	*–0.006*
13	10.000	–5.000	9.995	–4.992	*0.005*	*–0.008*
14	10.000	0.000	9.998	–0.018	*0.002*	*0.018*
15	10.000	5.000	9.998	4.994	*0.002*	*0.006*
16	10.000	10.000	10.003	10.003	*–0.003*	*–0.003*
17	–10.000	10.000	–10.010	9.986	*0.010*	*0.014*
18	0.000	0.000	–0.006	–0.010	*0.006*	*0.010*

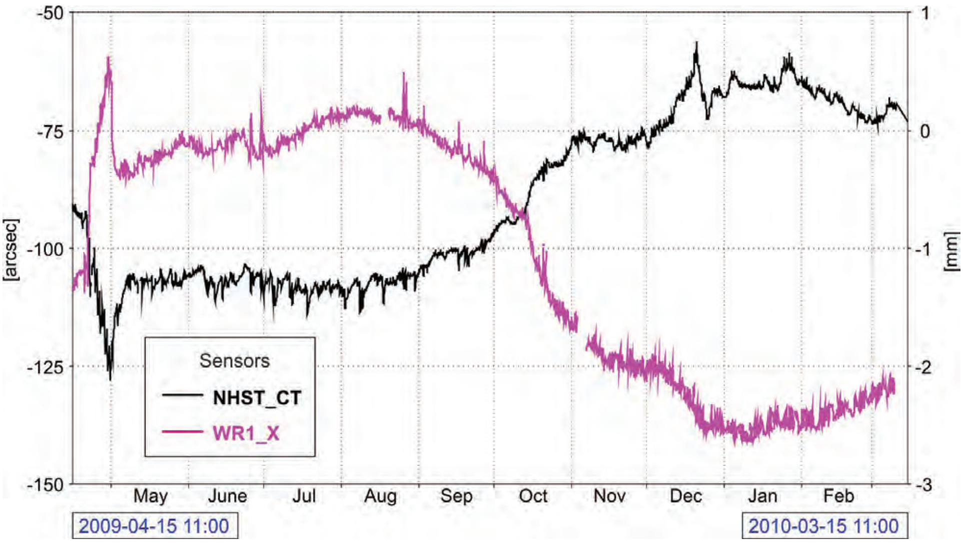

Fig. 6. The results of measurements taken using the laser device at a hydro-technical facility

Table 3. Results of the laboratory tests of the inductive device [mm]

No	X_s	X_p	X_p(n–1)
1	–4.0	1.36	0.49
2	–3.5	1.85	0.52
3	–3.0	2.37	0.53
4	–2.5	2.90	0.48
5	–2.0	3.38	0.47
6	–1.5	3.85	0.49
7	–1.0	4.34	0.53
8	–0.5	4.87	0.48
9	0.0	5.35	0.48
10	0.5	5.83	0.49
11	1.0	6.32	0.53
12	1.5	6.85	0.48
13	2.0	7.33	0.47
14	2.5	7.80	0.50
15	3.0	8.30	0.53
16	3.5	8.83	0.53
17	4.0	9.36	

Table 2 shows the measurement readings only on the X axis, since changes in the readings on the Y axis proved insignificant.

Figure 6 shows the measuring results of the laser device for measuring the pendulum wire displacement (violet), performed at a hydro-technical facility over a period of one year. In the first stage of the measurements large deformation of the object can be observed. It was correlated with the complete emptying of the tank and its filling after technical inspection. The variations in the object deformation recorded over the entire measuring campaign reflect the effects of the normal exploitation of the object, i.e. periodic drain water from the water reservoir and then refilling it as a regular. Long periodic sinusoidal deformation is due to seasonal changes of water temperaturę. The measured structure deformations amounted to about 3 mm. Their nature is similar to the nature of the mirror reflection of changes recorded using a hydrostatic levelling instrument (black). The frame of reference defining the direction of displacements of the laser device was not synchronized with the appropriate frame of reference of the hydrostatic levelling instrument (Table 2).

The device for measuring the pendulum wire displacements with a rotating laser beam was presented at the IWIS 2010 exhibition of inventions in Warsaw, where it was awarded a medal.

The inductive device for measuring the pendulum wire displacement was also examined at a new test stand of measuring range of 40 mm, and part of these tests was presented in Table 3.

In Table 3, X_s stands for the reference pendulum wire displacements by 0.5 mm in the range of 8 mm, whereas X_p stands for the values measured using the inductive device for measuring the pendulum wire displacements.

The difference between successive measurements taken using the inductive device was presented in column X_p(n–1).

The differences between the reference readings and those of the inductive device do not exceed plus/minus 0.03 mm, and constitute accuracies sufficient when measuring structure displacements and deformations with the measuring range of 40 mm.

4. Conclusions

The results of the laboratory tests and those conducted at the hydro-technical facility clearly indicate that the devices presented can be used for taking measurements in field conditions, and work in the automated measuring system existing in a structure, taking measurements of the pendulum wire displacements at the same time as instruments measuring parameters such as temperature, humidity, water level, the width of expansion joints, inclination, date, time, etc. Simultaneous measurements of all parameters enable a more accurate and faster analysis of correlations between the measured parameters at the controlled structure (Janusz and Janusz, 2005).

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Urządzenia do automatycznego pomiaru przemieszczeń drutu wahadła

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Streszczenie: W artykule opisano konstrukcję i zasadę działania dwóch prototypowych urządzeń: urządzenia laserowego i urządzenia indukcyjnego, służących do pomiaru przemieszczeń drutu wahadła. W pierwszym urządzeniu zastosowano wirującą wiązkę laserową oraz dwa detektory wewnętrzne (stałe) i dwa detektory zewnętrzne. Wiązka laserowa padając na detektory powoduje wygenerowanie przez nie sygnałów elektrycznych. Różnice czasowe wygenerowanych sygnałów przez detektory wewnętrzne (stałe) i detektory zewnętrzne są funkcją przemieszczenia drutu wahadła. W drugim urządzeniu zastosowano czujniki indukcyjne zamocowane w głowicy pomiarowej, która jest przytwierdzona do wózka krzyżowego, który przesuwa się wzdłuż prostopadłych do siebie osi *X* i *Y* w zakresie 50 mm. Wózek jest przesuwany silnikami krokowymi a umieszczone w osiach *X* i *Y* czujniki indukcyjne wyszukują położenie drutu wahadła. Liczba kroków silników krokowych jest miarą przemieszczenia drutu wahadła wzdłuż osi *X* i *Y*.

Urządzenia takie są stosowane do kontroli odchyleń od pionu wysokich obiektów hydrotechnicznych głównie na skutek działania naprężeń wewnętrznych i czynników zewnętrznych jak temperatura i poziom wody w zbiorniku.

Słowa kluczowe: odchylenie od pionu, pomiar przemieszczeń, wahadło, drut wahadła, obiekty hydrotechniczne

INSTRUCTIONS TO AUTHORS

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