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THE TECHNIQUE OF DETERMINING THE SMALL ANGULAR DEVIATIONS BY AN ELECTROSTATIC SENSOR

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Abstract. Some methods for determining small angular deviations have been considered on the example of building objects. The design of an electrostatic cylindrical sensor was put forward, and the use of force action of an electric field was proposed in order to increase the sensitivity of the sensor. The main structural elements of the sensor are a plumb-line weighted at one end and a cylinder surrounding it. The conditions of equilibrium and instability of the position of the plumb arising due to positive feedback in the electric field were considered. An estimated calculation of the time of movement of the plumb until the moment of its touching the inside of the cylinder was made. The calculation result could be taken as a starting point for finding the desired angular deviation. The inaccuracy in the manufacture of the device and the random factors were noted to become influential at small deviations. The paper proposed some ways to solve these problems.

Keywords: angular deviation, roll, electric field, electrostatic force, unstable equilibrium, motion time, calculation

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СПОСОБ ОПРЕДЕЛЕНИЯ МАЛЫХ УГЛОВЫХ ОТКЛОНЕНИЙ С ПОМОЩЬЮ ЭЛЕКТРОСТАТИЧЕСКОГО ДАТЧИКА

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Аннотация. Рассмотрены некоторые методы определения малых угловых отклонений на примере строительных объектов. Предложена конструкция электростатического цилиндрического датчика, для повышения чувствительности которого использовано силовое действие электрического поля. Основными элементами конструкции датчика являются подвешенный на нити груз и окружающий его цилиндр. Рассматриваются условия равновесия и нестабильности положения груза, возникающего за счет положительной обратной связи в электрическом поле. Выполнен оценочный расчет времени движения груза до момента касания внутренней части цилиндра, на основании которого может быть найдено искомое угловое отклонение. Отмечено, что при малых отклонениях становятся существенными неточность изготовления устройства и влияние случайных факторов. В работе предложены способы решения этих проблем.

Ключевые слова: угловое отклонение, крен, электрическое поле, электростатическая сила, неустойчивое равновесие

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Introduction

Deformation generally occurs in buildings and structures during operation due to a wide variety of factors, both natural and man-made. Natural factors may include the changing weather conditions (wind, snow, ice loads), the properties and composition of the soils under the building, etc. New construction sites near existing buildings may be the source of man-made deformation.

Deformations can be divided into vertical (in particular, shrinkage) and horizontal (for example, shear). Another classification is uniform and nonuniform deformations. Uniform settlement means that the building settles by the same value that does not affect the overall strength and stability of the structure. If the soils under the foundations have different compressibilities, then, due to different loads applied to them, the settlement of individual parts of the foundation will be uneven. This type of deformation is considered the most dangerous, since it can produce tilting, leaning or cracking within the building.

One of the approaches to controlling deformations involves periodic geodetic observations performed using levelers, laser scanners and total stations. Photogrammetric surveys and satellite technologies are also used. Levelers are typically used to determine settlements and deflections, electronic theodolites and total stations are used to determine the tilt. Lateral leveling is used to determine the verticality of the walls. A less accurate method is to measure the distances from the wall of the building to the line of the plumb attached to the top of the wall or on the roof with a standard ruler. In this case, the deviation is determined by the difference in the distances measured at the base of the wall and at its upper points. The accuracy of this settlement measurement varies from 1 mm to 1 cm, depending on the type of structure. The measurement accuracy is increased to tenths of a millimeter for settlement monitoring in buildings with stringent requirements to preservation and maintenance.

The so-called geodetic network is a method for deformation analysis in buildings, consisting of reference stations located outside the deformation zone and survey markers placed in the building. In this case, both absolute and relative types of deformations can be monitored.

The most common problem is measuring the small angular deviations of objects from the initial (for example, strictly vertical) position. Various techniques and sensors have been developed for these measurements. For example, a technique for measuring the shell tilt in bridge supports from one station is considered in [4] by comparing the difference between the measured vertical angles and their design values.

The linear component of the tilt is S_x found by the formula

$$S_x = H \cdot \frac{\gamma_x}{\rho}, \tag{1}$$

where H, mm, is the height of the shell, γ_x, rad, is the angular component of the tilt, ρ, ″, is the number of arc seconds per radian.

Projecting the point O of the structure center with an inclined horizontal axis to the vertical plane gives the height of the tilt i.

Monograph [9] describes various methods for determining the verticality of walls:

lateral leveling with a theodolite,

measuring the distances from the building wall to the heavy plumb line or to a tape measure with the plumb suspended from a console mounted on top of the wall or on the roof.

Wall tilt in the Novosibirsk Hydroelectric Station dam was measured in [8] by Nivel 220 inclination sensors combined with a total station. A method for measuring the wall inclination using total stations was proposed for single-chamber locks.

Determination of Cartesian coordinates and angles of building was carried out in [10] in real-time RTN GNSS mode by the HMM algorithm.

Modern approaches to determining the geometric parameters of chimneys are considered in [11]. Precise total station measurements were performed to find the control values for the geometric parameters of a chimney; the results obtained were used to assess applicability of the photogrammetric approach.

Only relative deformations are determined in the absence of reference points. However, it is sometimes impossible to apply geodetic survey methods for a structure. For example, scaffolding installed for restoration or reconstruction projects can cover most of the object, making surveys complicated. In this case, other devices and methods (in particular, non-geodetic) have to be used to determine the deformations in such buildings. Moreover, it is often necessary to monitor small-magnitude deformations. Such devices as inclinometers, crack gauges, tilt sensors installed directly on the structure are used for these purposes.

Tilting is a very common type of deformation in buildings [1, 3], posing huge potential risks, if safety measures are not in place. If tilting is detected, steps should be taken to stop its progression. A crucial factor to be taken into account is the direction of the tilt.

Thus, it is important to determine the direction of vertical deviation at small angles. Since the initial tilts are typically small, highly sensitive meters should be used. One of the possible solutions to this problem is using the force action of an electric field (EF) (see our earlier studies [5, 6]). While EFs are widely used in converters and sensors [2], we failed to uncover any reports on the force action of the EF for the applications considered in this study.

After tilting is detected and immediate action is taken, it is essential to determine both the direction and the magnitude of the tilt. The above studies were aimed at developing methods and devices for finding only the direction but not the magnitude of the deviation, which is also a major parameter to be considered.

Therefore, the goals of this study consisted in developing a methodology allowing to determine the deviation magnitude with the device developed earlier. Furthermore, we intended to calculate the quantitative estimators for this quantity.

We should emphasize that the calculations presented are purely simplified estimates serving to evaluate the order of the given quantities from the results obtained. In addition, the results should confirm whether it is feasible (or not) to implement the proposed method in practice. Large-scale experimental studies are required to fully integrate the theory underlying study and validate the method.

Design of the sensor and its operating principles

The design and operating principles of the device were discussed in detail in earlier studies. In particular, it was confirmed in [5] that a cylindrical plumb suspended on a string in a round hollow cylinder (tube), placed in an electrostatic field (Fig. 1,*a*) can be used to solve the problems posed. These elements must be electrically conductive or semi-conductive, while the plumb line must be isolated from the cylindrical tube. When a small tilt appears, the line becomes nonparallel to the walls, forming a small angle with them α_0. The EF can be generated between the cylindrical plumb and the cylinder walls by applying a constant electric voltage U to the cylinder and the plumb. Given the deviation of the plumb by the angle α_0, the distance between the plumb and the cylinder wall decreases in the deviation direction and increases in the opposite direction. As a result, the force of attraction generated by the EF increases in the direction of deviation decreases and in the opposite direction. Therefore, the deviation of the plumb increases. If the applied voltage exceeds some critical value, then the restoring force cannot compensate for the electrostatic forces of the EF. The plumb then continues to deviate until it touches the cylinder wall in the deviation direction. It is easy to determine the deviation direction by experimentally measuring the position of the point where the plumb touches the cylinder wall. This measurement technique is considered in [5]. The study also presents calculations for the forces generated by the EF, the restoring forces and their resultant action, leading either to a stable or an unstable position of the plumb.

In contrast to Fig. 1,*a*, Fig. 1,*b* shows the situation in the reference frame associated with the walls of the cylindrical tube. The dotted line shows the initial position, the dash-dotted line shows the position of the plumb with a slight tilt; the bold dashed line shows the equilibrium position in the presence of an EF between the plumb and the tube. Since the deviation angles are small, the approximation of parallel-plate capacitor can be used in the calculations.

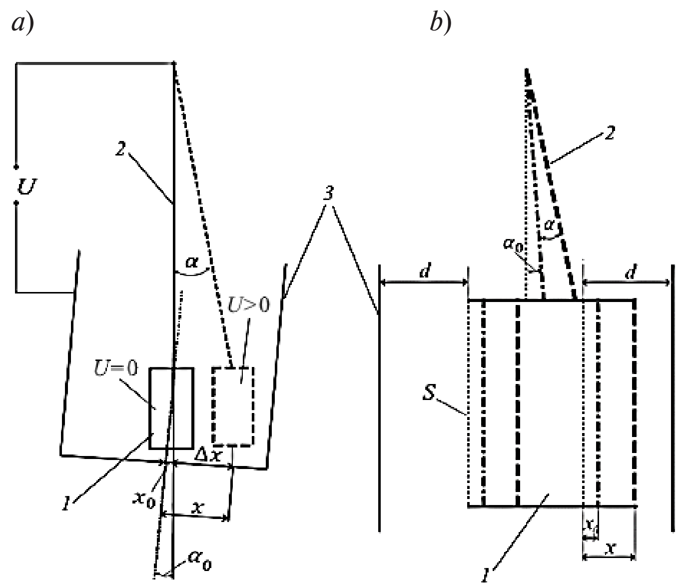

Fig. 1. Schematics of the device (*a*) and its model for calculating the effect of the electric field on the plumb deviation in the reference frame associated with the walls of the tube and cylinder [7] (*b*);
plumb *1*; line *2*; cylinder *3*; electric field potential U between the plumb and the cylinder walls; α is the plumb-line deviation angle

An expression was obtained in [5] for the electrostatic force generated by the EF and acting on the plumb:

$$F_e = 2\varepsilon_0 \varepsilon S U^2 \frac{dx}{\left(d^2 - x^2\right)^2}, \tag{2}$$

where x is the deviation of the plumb from the initial position due to the combined action of the external tilt, producing the deviation x_0, and of the electrostatic forces; d is the gap between the tube wall and the plumb before the tilt; ε_0 is the vacuum permittivity; ε is the dielectric constant of the liquid between the cylindrical tube and the plumb; S is the effective area subjected to the pulling force; U is the electrical voltage applied between the plumb and the cylinder,

It was established in [5] that if the voltage is less than a certain critical value, then as a result of balance of electrostatic force, gravity and Archimedes force, the plumb deviates by a noticeable angle α. The magnitude of the angle α is significantly larger than in the case when voltage is not applied.

Different scenarios can evolve with the stability of the plumb position depending on the intensity of the EF generated [5].

Next, we consider the situation when a voltage exceeding a critical value is applied between the plumb and the cylinder wall. The latter guarantees that motion of the plumb towards the cylinder wall is uninterrupted until it touches the wall. This value was calculated in [5] and follows the expression

$$U_{kk} = \sqrt{\frac{\left(mg - \rho g V\right) d^2}{2\varepsilon_0 \varepsilon S l}}. \tag{3}$$

where ρ, g/l, is the density of the damping fluid in which the plumb is placed; V, cm^3, m, g, are its volume and mass, respectively; g, cm/s^2, is the gravitational acceleration.

The corresponding voltages for the real values of the quantities included in expression (3) are tens of volts, which is quite acceptable for practical applications.

Notably, the resulting electrostatic force is small at small deviation angles, and, accounting for the inertia of the plumb and the viscosity of the medium, it takes a certain time for the plumb to move to the tube wall. This time interval is apparently the longer the smaller the initial deviation of the plumb line from the vertical. Thus, if we measure the time from the instant when the voltage is switched on to the instant when the signal appears in the signal elements detecting contact between the plumb and the wall, we can assess not only the direction but also the magnitude of the initial deviation. This is the gist of the technique proposed for measuring the deviation angle. The idea is well justified physically, as confirmed by the patent obtained for it [6]. However, detailed analysis of this method still requires complex calculations and numerous experimental studies. In this paper, we confine ourselves to approximate quantitative analysis of the situation, primarily aiming to establish whether the concept described can be implemented in practice.

Estimation of motion time and deviation magnitude for the plumb

Let us estimate the time for which the plumb moves until it touches the tube wall.

For simplicity, we neglect the restoring force, assuming that if a voltage significantly larger than U_{kk} is applied, the restoring force is small compared to the electrostatic one, which is not difficult to verify by quantitative calculations based on the expressions obtained in [5]. Additionally, it should be borne in mind that Eq. (2) can be simplified for small values of x:

$$F_e = 2\varepsilon_0 \varepsilon S U^2 \frac{x}{d^3}. \tag{4}$$

Analyzing this formula, we can conclude that the electrostatic force increases hyperlinearly depending on x at values of x commensurable with d. However, this is not taken into account solely for the purpose of simplifying the calculations. An additional factor allowing to adopt such an assumption is the small value of x for a significant part of the total time for which the plumb moves until it collides with the wall, when the electrostatic force is small and, accordingly, so is the acceleration of the plumb. Thus, taking into account the simplifications adopted, the electrostatic force generated by the EF and acting on the plumb can be expressed as

$$F_e = kx, \tag{5}$$

where

$$k = \frac{2\varepsilon_0 \varepsilon S U^2}{d^3}. \tag{6}$$

Based on Newton's second law and expressions (4)–(6), the equation of motion for a plumb with mass m takes the following form:

$$m\frac{d^2x}{dt^2} = kx. \tag{7}$$

The solution of this differential equation is the function

$$x = x_0 e^{\left(\sqrt{\frac{k}{m}}\right)t}. \tag{8}$$

Let us calculate the motion time t_m of the plumb to the tube wall, i.e., consider the situation when $x = d$.

It follows from Eq. (8) that in this case

$$t_m = \frac{\ln\frac{d}{x_0}}{\sqrt{\frac{k}{m}}}. \tag{9}$$

In view of expression (6), we obtain from Eq. (9) the final expression for the motion time of the plumb from the instant when the electric voltage is switched on to instant when the plumb collides with the cylinder wall and the information signal appears:

$$t_m = \frac{\ln\frac{d}{x_0}}{\sqrt{\frac{2\varepsilon_0 \varepsilon S U^2}{md^3}}}. \tag{10}$$

On the one hand, the resulting expression gives an overestimated time value compared to the real one, since the electrostatic force increases faster with the motion of the plumb than was taken into account in the calculation. On the other hand, the viscous friction and the restoring force were not taken into account in the calculation (ignoring these forces produces an underestimated time value). In view of the above arguments, we take the resulting expression to be acceptable for a rough estimate of the required value.

Using expression (10), we find the deviation of the plumb x_0 due to by external causes based on the measured time value:

$$x_0 = \frac{d}{\exp\left(t_m\sqrt{\frac{2\varepsilon_0 \varepsilon S U^2}{md^3}}\right)}. \tag{11}$$

Based on the model adopted for calculating the effect of the electric field on the plumb deviation (see the schematic (not maintaining the aspect ratio) in Fig. 1,*b*), where the length of the string l is assumed to be much greater than the height of the plumb, accounting for the smallness of the deviation x_0, we obtain that

$$\alpha_0 = \mathrm{arctg}\frac{x_0}{l}\ \text{(rad)}. \quad (12)$$

Thus, the final formula allowing to determine the required deviation angle takes the form

$$\alpha_0 = \mathrm{arctg}\frac{d}{l\cdot\exp\left(t_m\sqrt{\dfrac{2\varepsilon_0\varepsilon S U^2}{md^3}}\right)}, \quad (13)$$

where d, mm, is the gap between the plumb and the cylinder wall at their initial coaxial position; l, mm, is the length of the string, t_m, s, is the measured motion time of the plumb to the cylinder wall; ε is the dielectric constant of the medium between the plumb and the tube; ε_0, F/m, is the vacuum permittivity, S, cm^2, is the area subjected to the pulling force; U, V, is the electrical voltage applied between the plumb and the cylinder; m, g, is the weight of the plumb.

The calculated results are given in the table.

Table

Calculated estimates for motion time of the plumb as function of its initial displacements and deviation angle of the plumb line (see Fig. 1)

x_0, μm	0.001	0.01	0.1	1	10	100
α_0, μrad	0.01	0.1	1	10	100	1000
t_m, ms	441	360	280	199	119	38

Notes. 1. The time t_m is counted from the instant when the electrical voltage is switched on to the instant when the information signal appears in the electrical circuit. 2. The values of the other calculated parameters are as follows: d = 0.3 mm, S = 10 cm^2, U = 100 V, ε = 2.5, m = 20 g, l = 10 cm.

To better the visualize the quantitative values of the given quantities, Fig. 2 shows an example dependence of the required deviation angle on the motion time of the plumb before collision with the wall at different voltages U. The dependence is calculated by Eq. (13) with the same values of the other parameters given in Note 2 to Table.

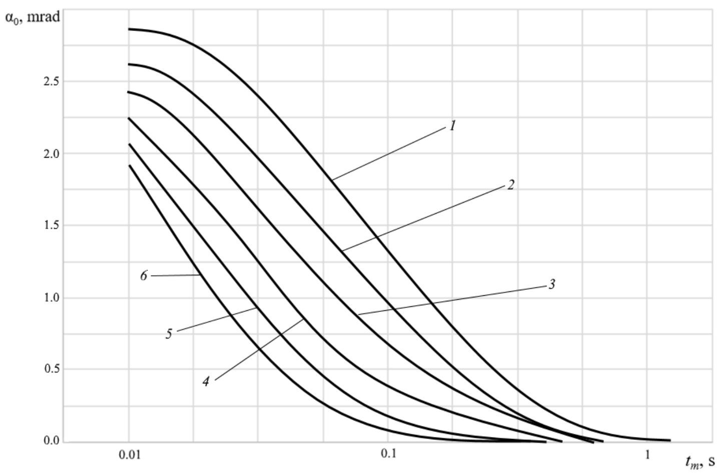

Fig. 2. Calculated dependence of required deviation angle for motion time of the plumb at different voltages U, V: 25 (*1*), 50 (*2*), 75 (*3*), 100 (*4*), 125 (*5*) 150 (*6*)

We can conclude from the data obtained that the device shows good operating speed. Moreover, the obtained values are relatively easy to measure with high accuracy and, therefore, allow recording very small deviations from the vertical (horizontal).

Practical application of the device

Recall again that the calculation was performed to provide estimates, so Eq. (13) should not be considered to be ready for practical use. A large number of experiments and, furthermore, constructing a family of calibration curves are required to determine the magnitude of the angular deviation in practice.

It was assumed above that the distances from the outer surface of the plumb to all points of the cylinder's inner surface are equal until the time when the plumb starts to deviate. However, this is not entirely correct, as the device has manufacturing errors. The influence of random factors (for example, vibrations) which can change the deviation of the plumb was also not taken into account. As evident from the operating principles of the device, it has strong positive feedback, so a random deviation due to unaccounted factors leads to a change in the direction caused by the action of these factors. It is also obvious that this circumstance is particularly significant for measurements of small deviations. We should then note that the device has a finite measurement accuracy, limited by its manufacturing technology and the influence of external factors. However, this does not mean that the device cannot function properly in practice. This problem has already been discussed in [5].

To summarize the main points,

firstly, vibrations can be minimized by increasing the weight of the plumb and strong damping;

secondly, a special procedure can be applied for measurements.

It consists of the following steps.

A position of the device in which the plumb is equally probable to deviate in all directions should be chose before the measurements. Thus, manufacturing inaccuracies and the influence of random factors are taken into account. The position found is taken as the initial one. A slight deviation of the load but with a specific characteristic direction appears in practical measurements as a result of the deviation from the vertical (for definiteness) due to the tilting of the structure. Even if this deviation is very small, a correlation is still be found with a large number of measurements between the direction and magnitude of the deviation and the sensor readings, pointing towards the required deviation direction. In this case, the value of the deviation angle can be calculated for a given direction using the expressions obtained.

Thus, pre-tuning is necessary before the device can be used in practice. Another important consideration is that the direction and magnitude of the tilt should be estimated from a series of measurements rather than a single run.

Conclusion

The benefit of the device proposed in this paper is that it can measure not only the direction, but also the magnitude of the deviation, even for a value tending to zero, due to the instability of the plumb position in the EF. This is a clear difference from other measuring devices with the same purpose, which are limited not only by the manufacturing accuracy and the influence of random factors, but also, crucially by the important circumstance that their sensitivity decreases with a decrease in the magnitude of the deviation, because of their physical operating principles. The capabilities of the given device are limited only by the manufacturing accuracy and random factors. Moreover, it takes the plumb the longest time to move to the wall specifically at small deviations, making the measurements more reliable.

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