HYDROSTATIC LEVELLING SENSOR FOR MONITORING HEIGHT SHIFTS OF BUILDINGS

J. Lechner [1] *, J. Drozda [1], K. Vach [2], A. Dlesk [2]

[1] VÚGTK, Research Institute of Geodesy, Topography and Cartography, Czech Republic - (jiri.lechner, jiri.drozda)@vugtk.cz
[2] EuroGV, spol. s r. o., Rudná, Czech Republic - (vach, dlesk)@eurogv.cz

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ABSTRACT:

On the basis of the requirement to solve the operational safety of important construction and energy objects in the Czech Republic and further on the basis of acquired knowledge and experience in ensuring the measurement of shifts of construction objects, the Geodetic, Topographic and Cartographic Research Institute in the Czech Republic, v.v.i. proceeded with the development of a sensor for measuring height shifts and its integration into an integrated measuring system. As part of the project BIM - Building Management II - development of IoT modular blocks for the digital twin of the building, co-financed by the European Union, a sensor based on hydrostatic levelling was developed with an accuracy of measuring height shifts of 0.1 mm, with a measuring range of up to 2.5 m between individual measuring sensors and with the possibility of its inclusion in an integrated measuring system. This contribution gives technical details about the developed sensor.

1. INTRODUCTION

The general issue of environmental protection necessarily leads to increased attention to the structural behaviour of building objects, and their structural parts, to the monitoring of physical factors affecting their stability, and to the functional and operational reliability of these objects. Rapidly developing areas of the economy, especially energy, transport, waste management, and the chemical industry, require the measurement of the dynamics of spatial changes in the geometric conditions of objects and technological equipment both during the construction process and during the operation of these facilities. The term shift and deformation means gradual changes of objects in spatial position due to their weight, dynamic operational effects, and other physical factors in a given environment and time. Measurements are used to determine the course, nature, and magnitude of these changes in relation to the initial state. Changes take place both in the horizontal and vertical directions. With different characteristics of building structures, building foundations, and subsoil, the buildings are tilted or the shape of individual structures changes.

Therefore, the purpose of monitoring shifts and deformations of building objects is to obtain the basis for assessing the behaviour of the foundation soils beneath the object, to compare actual shifts with theoretical values and verify the correctness the theoretical values, to monitor the condition, functional reliability and safety of the building structures, and to monitor the influence of various physical environmental factors on changes in the behaviour of the building structure. This information has scientific, technical, economic and security significance. The scientific importance of understanding the factors affecting the stability of the objects under study lies in the development of the theories of building foundations, soil mechanics, structural mechanics, design and the development of measurement theory. The technical importance lies in the possibility of refining construction technologies, and the economic and safety importance lies in taking measures to reduce damage, protect the environment and save human lives.

Measurements of shifts and deformations of structures can be carried out by various physical methods, of which geodetic methods provide comprehensive 3D spatial information about the behaviour of the inspected objects in relative or even absolute values. Measurement by the geodetic method of precise levelling has its predictive ability only for the time period when it was carried out. For these reasons, stationary systems that achieve the required measurement accuracy and provide real-time information are becoming increasingly important. A hydrostatic system appears to be the preferred monitoring system.

2. HYDROSTATIC LEVELLING

2.1 The principle of hydrostatic levelling

The theory of hydrostatics has been known for a very long time. This is evidenced by a number of solutions from before the beginning of our era. The literature describes a water levelling device that was used to lay out the "Pharaohs' Canal" in ancient Egypt some 2500 years ago to connect the river mouth of the Nile River to the Red Sea.

Hydrostatics deals with the study of fluids that are at relative rest. In order for a fluid to be at rest, all the forces acting on the fluid must be in equilibrium, and fluids transmit so-called compressive forces, i.e. not classical point forces as in the case of solids, but forces on a surface. In hydrostatics, two laws are valid Archimedes' law, which states that an object immersed in a fluid experiences a buoyant force that is equal in weight of the fluid displaced by the object, and Pascal's law, which states that if an

* Corresponding author

external pressure force is applied to a liquid, then the pressure at each point in the liquid will increase by the same amount. This fact is used in hydrostatic measuring systems, where in connected vessels the liquid is transferred from one to the other until hydrostatic equilibrium is reached.

2.2 Available solutions for hydrostatic measuring systems

Hydrostatic systems differ in design, liquid type, measuring range, accuracy and liquid level indication, and are divided into two groups, digital and analogue. Depending on the method of registering the liquid level position, measuring systems are divided into contact, float, capacitive, frequency, electro-optical, photoelectric, fiber optic, etc. In connection with the increasing power output of nuclear power plants, the requirements for the number of inspection points on their sites and the frequency of individual measurement cycles are increasing. That can only be achieved by fully automating the measurement processes. An important factor in the development of engineering-geodetic monitoring of important engineering structures is the actuality and objectivity of information about their condition in real-time with an emphasis on increasing the real accuracy of measurement, which can only be ensured by the application of automated technologies. In Germany, Freibereger Präzisionsmechanik offers the FG-ASW 101N automated precise hydrostatic system with a measuring range up to 45 mm and a resolution up to 0.02 mm. In the technical conditions, the accuracy is not mentioned but the measuring system is based on the measurement of the height of the liquid levels and therefore the accuracy of the measurement depends on the temperature regimes. Another system is, for example, the Glötzl hydrostatic system GHD 4 with a resolution of up to 0.01 mm, a measuring range of 20 cm and a linearity of 0.2%. The measurement accuracy is also dependent on compensation for temperature differences within the measuring system.

Another example of the application of a hydrostatic system for monitoring the height deformation of technologies is the device for the implementation of collision experiments and electron monitoring at the particle accelerator at CERN, Switzerland. At the world's largest particle physics centre at the world's largest particle accelerator, the Large Hadron Collider, a task for surveyors was also carried out, which consisted in very precise delineation of the individual components of the accelerator, in control measurements of the position and height of its individual segments, in documenting the actual state, and now ensuring that all its technology is continuously monitored to study muons. Again, a device was used to register the position of the liquid level in the system. However, it should be noted that the technology itself is located at a depth of about 90 m underground, i.e. the temperature conditions here are practically constant.

2.3 Advantages of the hydrostatic technology for measuring deformations of objects

The technology itself enables the realisation of stationary systems with the possibility of repeating measurements (staged measurements) of deformations in real time, than it is possible to get information about the geometric state of the construction objects and technologies virtually and instantaneously. The hydrostatic technology gives the possibility to positively influence the operating mode of the device almost immediately and to eliminate degradation of the equipment due to the possibility of geometry optimization (adjustment). By optimising the operation of the equipment, the time between major overhauls of the equipment is extended, i.e. the economy of operation of the equipment is increased. As a result of the optimisation of the operation, the safety of the operation and thus the health and safety of the workers is increased. As another advantage, it can be stated that the hydrostatic technology can also be used in environments with vibrations, as the fluid absorbs these vibrations. The use of hydrostatics technology ensures a uniform height system (coordinate system) within the entire measuring system, which is not possible with electronic sensors based on other measuring principles.

2.4 The accuracy of the measurement by hydrostatic technology

The accuracy of the measurement of shifts of structures is characterized by the value of the limiting deviation of the determination of the length of the resulting shift vector or its component (ČSN 73 0405):

$$\delta_1 = \frac{2}{15} p, \quad (1)$$

Where p is the expected total shift or its component in millimeters. For equipment with increased demands on its consistency, reliability, safety and economy of operation, the value of the limit deviation δ_1 hall be set individually $\frac{1}{3}$ stricter, , unless the designer specifies otherwise. The value of the limit deviation for the measurement of shifts of buildings in use affected by construction activities in the surroundings shall not exceed the value of:

$$\delta_2 = \frac{2}{5} p_k, \quad (2)$$

Where p_k, is the critical shift value in millimeters at which the monitored object is in danger. The actual accuracy of the measurement is also derived from the tolerances for e.g. the tilt of the reactor building (tilt of the base plate under the reactor) or the relative height change of the turbine-generator rotation axis.

The most strict accuracy criterion, e.g. for the reactor building and the turbine-generator building in nuclear power plants with a capacity of 1000 MW, is a requirement to meet the limit deviation criterion in height and in operation of the TG of 0.2 mm at the axis of the turbomachinery, namely at the bearings between the low-pressure part NT3 and the generator. If this criterion is to be fulfilled or demonstrated on the basis of the measured data, the measurements must be made with an accuracy characterized by a standard deviation of the elevation measurement of at least 0,04 mm. This accuracy is very difficult to achieve in the conditions of TG operation (high temperature, vibrations, the necessary time for measurement - if the technology of very precise levelling is considered because the levelling procedure around the TG part takes about 4 hours and it is not possible to ensure the invariability of the position of the controlled points on the turbine-generator technology throughout this time. Another parameter assessed is the cyclicity of the measurement with an impact on obtaining up-to-date information on the height state of the measurement object.

3. HYNI – DEVELOPMENT OF THE STATIONARY AUTOMATED HYDROSTATIC MEASURING SYSTEMS

On the basis of the accuracy requirements for the stability (in the height sense) of the technological equipment and structural parts of the power plant machinery, the Research Institute of Geodesy, Topography and Cartography in the Czech Republic) dealt with tasks related to solving the problem of geodetic support for the construction of nuclear power plants within the framework of international cooperation of the geodetic services of the USSR, the GDR and the Czechoslovakia. The Czech party had the task to elaborate the problem of technical solution of the measurement of height deformations of structural and technological objects of nuclear power plants. This part of the solution was documented in detail in the joint publication Technology of Geodetic Security for Nuclear Power Plant Construction (Unknown, 1985), which also includes the area of construction surveying, prepared by the geodetic service of the GDR. For the actual solution, it was decided to develop a measuring system with sensors whose measurement accuracy is no longer dependent on the temperature of the liquid and the sensors themselves are resistant to the harsh environment, i.e. they can be installed directly into the industrial environment. Because of that, HYNI and INVA technologies were developed. The measurement accuracy of the systems was characterised by a standard deviation of 0.05 mm of the elevation measurement within the whole measuring system (up to a maximum distance of 100 m) $\sigma \leq \pm 0.05\ mm$.

Figure 1. A view of the bearing between the low pressure parts of the turbine with orange bracket for HYNI measuring sensor.

Figure 2. A view of the exposed rotor of the high-pressure part of the turbine with orange bracket for HYNI sensor.

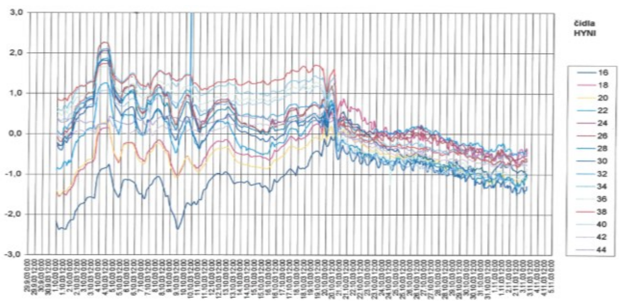

Figure 3. Recordings by the HYNI system with capture of the change in the turbogenerator operation mode (values are in mm).

In recent years, the issue of the need to understand the behaviour of the foundation soil due to the effect of the building, nearby objects and other activities in the vicinity and to monitor the function and safety of the buildings in operation has become an inevitable requirement. There are many examples where it is not possible to implement a classical hydrostatic measuring system with a single height level solution for monitoring the height deformation of a building. Therefore, it was decided to solve the project "BIM – FACILITY MANAGEMENT II - Development of modular IoT blocks for the digital twin of the building", namely the development and production of a levelling sensor for monitoring vertical shifts/deformations of buildings with sub-millimetre accuracy. The sensor system was integrated into a central integrated system with communication via RS 485 bus. A unique and completely new benefit of the solution is the possibility of using sensors within the total measuring range of up to 2.5 m, the accuracy of measuring relative height shifts characterized by a standard deviation of 0.2 mm and the independence of the measurement itself from changes in ambient temperature. The stationary hydrostatic measuring system therefore consists of hydrostatic sensors connected by liquid hoses and cables for data transmission and power supply and a control unit (PC) with the appropriate equipment for communication with the sensors via RS 485 bus. The number of sensors in the measuring system is determined on a case-by-case basis and a maximum of X x 32 sensors can be connected to the system. The evaluation of individual shifts is automated based on the determination of reference points, and the height stability of the reference point itself is also assessed based on the analysis of the measured data. An important feature of the measuring system is continuous measurement without operator intervention. Data collection takes place at predefined time intervals and the measured values can be viewed at any time while the measuring program is running automatically.

Physical dimension	220x200x80 mm
Power supply	18-30 V, 0.1A
Range measurement	0.1 – 2500 mm
Communication	RS 485 – two-wire connection

Table 1. Technical data sheet of the sensor.

Figure 4. The hydrostatic sensor.

Figure 5. Configuration of the hydrostatic sensors in the real testing object.

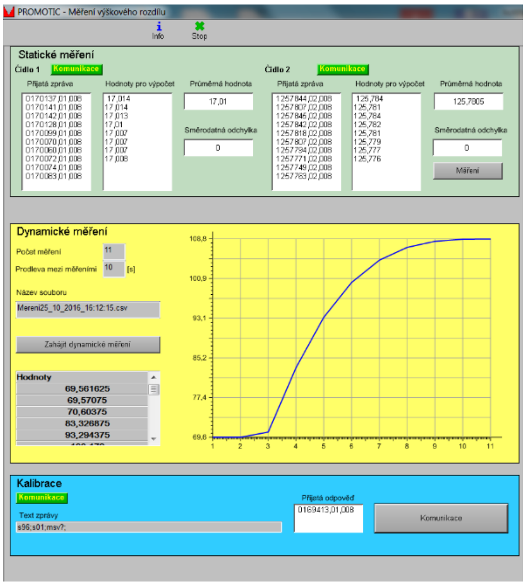

Figure 6. Verification tests of the measuring system (8 sensors) with hydrostatic settling time pressure of the system for about 60 seconds.

4. CONCLUSIONS

On the basis of the problem solved in the project co-financed by the European Union was developed, hydrostatic levelling system with sensors for monitoring of height deformations of the controlled sites with their mutual elevation up to 2.5 m was developed and verified. The accuracy of the measurement of height deviations is characterised by a standard deviation of $\sigma \leq 0.2\ mm$.

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