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OPTICAL MONITORING SYSTEM FOR SETTLEMENTS AND INCLINATIONS

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Abstract: A novel laser-based concept for monitoring settlements as well as inclinations of bridge piers over long periods of time is presented. Similar to the well known water leveling equipment the new system consists of several modules, which can be fixed and adjusted by simple means at the piers. Each module includes a laser source, optical components for beam forming and splitting and two position sensitive detectors. Two emitted and two incident horizontal beams in opposite directions "interconnect" each module to its neighbors. Details are given about the mechanical and optical layout, the operational performance, especially with regard to influences of beam length and turbulent air. The uncertainty of results is investigated both by experiments and numerical simulation.

Keywords: monitoring, settlement, inclination, experimental mechanics

1 INTRODUCTION

The safety of large structures depends – among other factors - on the properties of the ground. Local differences in settlement may cause inclinations or induce damaging forces into the structure. A suitable method to avoid potential dangers of damage as well as costly reconstruction is automatic monitoring. Up to now only hydrostatic leveling systems [1; 2] have been used for this purpose. Well approved laser-based instruments [3-6] are not applicable for long-term monitoring.

2 DESCRIPTION OF THE NEW METHOD

The development is based on experience gained with an earlier system [6] comprising one single laser source and a limited number of position sensitive detectors (PSDs), which are exclusively applied for measuring deflection lines of single bridge fields. The new system is also applicable for multiple field bridges. It makes use of the proven sensor principle, but instead of only one central laser source each module includes its own laser.

2.1 Modular system

Figure 1 shows schematically a section of the bridge equipped with the new system. Sensor modules are fixed at the piers, each of them "interconnected" optically to its neighbors by two emitted and two incident laser beams. Settlements as well as inclinations of the piers can be calculated separately from relative displacements of the incident beams as will be shown below.

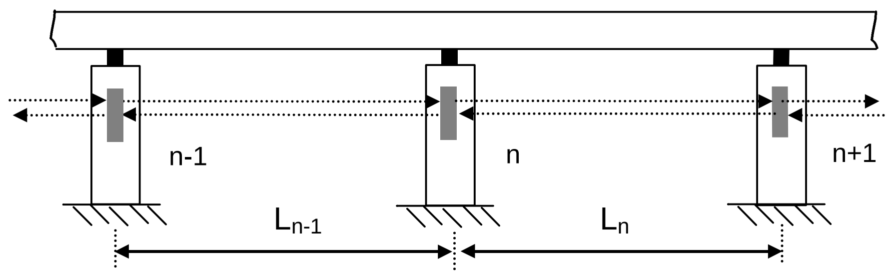

Figure 1. Instrumented bridge piers

2.2 Modules

As depicted in figure 2 a common laser beam is split into two horizontal beams emitted in opposite directions. The module also receives a beam from its neighbors. The positions of the incident beams are measured by means of two position sensitive detectors (PSDs). All laser sources (laser diodes, 14 mW, 685 nm) are modulated by the same clock. Modulation is necessary in order to avoid the influence of stray light. A cylindrical lens is used to form a line instead of a spot allowing easier adjustment.

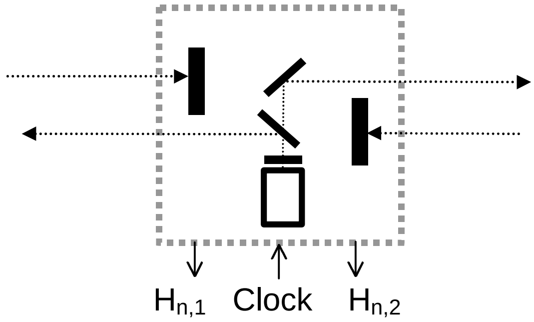

Figure 2. Module n including: laser, cylindrical lens, beam splitter, mirror and two PSDs

2.3 Position sensors and signal conditioners

The sensors are one-dimensional position sensitive detectors (PSD). Referring to figure 3 the sensor comprises an array of discrete, equidistant photodiodes and a chain of equal resistors. The length of the chain is 120 mm. The overall performance of this circuit corresponds to the well-known lateral-effect-PSD (Wallmark-diode). The output signals of both types of sensors require the same signal conditioning: The asymmetry of the output currents – symbolized in figure 3 by arrows of different length – corresponds to the eccentricity of the beam in relation to the diode chain. The difference of the output currents has to be divided by their sum and multiplied by half the length of the diode chain to get the displacement from the center position. The resolution is better than the rough pitch of the chain. Interpolation is based on the broad beam profile with smooth slopes. A detailed analysis of the interpolation method has been published earlier [6].

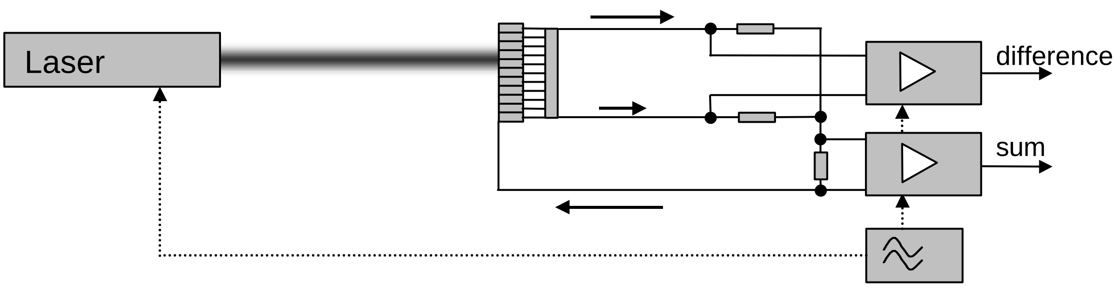

Figure 3. position sensing and signal conditioning

In order to minimize the influence of daylight or light from other sources it is necessary to use modulation. For this purpose ordinary strain gauge equipment can be applied. Commercially available carrier frequency instruments are able to suppress superimposed DC- or low-frequency components, even if their levels exceed the signal by orders of magnitude. Three single resistors convert the currents into voltage signals, which are fed into the differential inputs of two carrier-frequency amplifiers, so that difference and sum are amplified separately. The ratio of both is calculated in a PC. The common oscillator controls the laser as well as the phase selective detectors within the amplifiers. Since one laser irradiates two sensors, four amplifier channels have to be synchronized. With regard to the large number of channels, a data logger with low-level multiplexer is an economical solution.

2.4 Theory of data processing

The bridge may have N supporting points, the first (1) and the last (N) are supposed to have a constant height. The height profile is approximated by a linear interpolation, i. e. a polygon joining all supporting points. If a settlement takes place, the difference in slope at point n changes by an amount ΔS_n given by equation 1:

$$\Delta S_n = -\left(\frac{H_{n-1,2}}{L_{n-1}} + \frac{H_{n+1,1}}{L_n} \right) \qquad \text{for n = 2, 3, ... N-1} \tag{1}$$

The settlement ΔY_n of point n can be calculated by "numerical integration":

$$\Delta Y_n = \Delta Y_{n-1} + L_n \cdot \sum_{m=1}^{n-1} \Delta S_m \qquad \text{for n = 2, 3, ... N-1} \tag{2}$$

where the only missing term, ΔS_1, can be found by applying $\Delta Y_1 = \Delta Y_N = 0$:

$$\Delta S_1 = -\frac{\Delta S_2 \cdot (L_2 + \ldots + L_{N-1}) + \Delta S_3 \cdot (L_3 + \ldots + L_{N-1}) + \ldots + \Delta S_{N-1} \cdot L_{N-1}}{L_1 + \ldots + L_{N-1}} \tag{3}$$

In a similar way the change in inclination ΔI_n of pier n can be determined by

$$\Delta I_n = \frac{\Delta Y_n - \Delta Y_{n-1} - H_{n-1,2}}{L_{n-1}} \tag{4}$$

3 UNCERTAINTY

Any result is incomplete without additional information about its uncertainty. Methods to determine uncertainty are described in detail in the ISO guide [7]. In the case described here the following two questions must be answered: What are the essential sources of uncertainty related to measured displacements? How do they contribute to the uncertainty of results, namely settlements and inclinations?

3.1 Sources of uncertainty

The main sources of uncertainty are listed below in the sequence of their importance beginning with the worst:

a) turbulent air, especially near hot objects,
b) mechanical noise caused by shock waves and vibration in the ground, which can cause...
c) irreversible deformations in fixtures of modules or their internal optical components,
d) deformations of optical components due to changes in temperature or humidity,
e) fluctuations of the laser beam angle or its profile caused by temperature or degradation within the laser diode,
f) daylight, light from other sources,
g) smoke and fog,
h) deposition of dust or dew on optical surfaces,
i) imperfections of sensors and signal conditioners, such as noise, offset and non-linearity.

In most applications only the low-frequency components of settlement and inclination are of interest. Dynamic measurement is principally possible, but in general at an essentially higher noise level within in the frequency band of interest (0,5 – 20 Hz) due to influences a) and b). In any case analog low-pass filtering or digital averaging is recommended. Lowest possible cut-off frequencies should be selected, e. g. 0.1 Hz for static and 10 Hz for dynamic measurement.

The stability of optical and mechanical components (influences c and d) requires careful design and choice of materials with respect to their linear expansion coefficients.

Optical interference by daylight or light from other sources f) can occur if the illuminance exceeds that of the laser light by orders of magnitude. The effect of which can drive the sensor circuit into saturation. By placing a slot-shaped entrance window at a sufficient distance from the diode chain the sensor's field of view is drastically limited, thereby reducing this influence. In extreme environmental conditions it is recommended to take measurements at night, not only with regard to the absence of daylight. The levels of many other sources of uncertainty, such as turbulent air, shock and vibration as well as all temperature induced deformations are essentially lower at night.

The majority of the above listed sources of uncertainty become more critical with increasing beam length. The uncertainty of the local position of the illuminated area increases. In contrast the illuminance and hence the signal-to-noise ratio decreases.

For long-term field tests under "normal" conditions the standard uncertainty of displacement sensing is approximately

$$U_d \approx 0.2 \text{ mm} + L \cdot \frac{0.1 \text{ mm}}{10 \text{ m}} \tag{5}$$

where L is the length of the laser beam.

3.2 Uncertainty of results

Figure 4 depicts a typical situation, where one pier of a bridge has settled by a certain amount and another one is inclined by a certain angle. Points number 1 and 6 are assumed to be fixed. As a response to settlement and inclination some of the sensors detect displacements which are listed in the caption of figure 4. Applying equations (1) through (4) this set of input signals generates the precise set of output signals ΔS_3 and ΔI_4 - assuming that the uncertainties of measured displacements are insignificant. In this case there is no "crosstalk" - neither between the two different input variables nor between the results obtained at different piers. The indicated settlement of point number 3 does not depend on inclination occurring at point 4 and vice versa, as long as all displacements remain within the sensors' linear ranges.

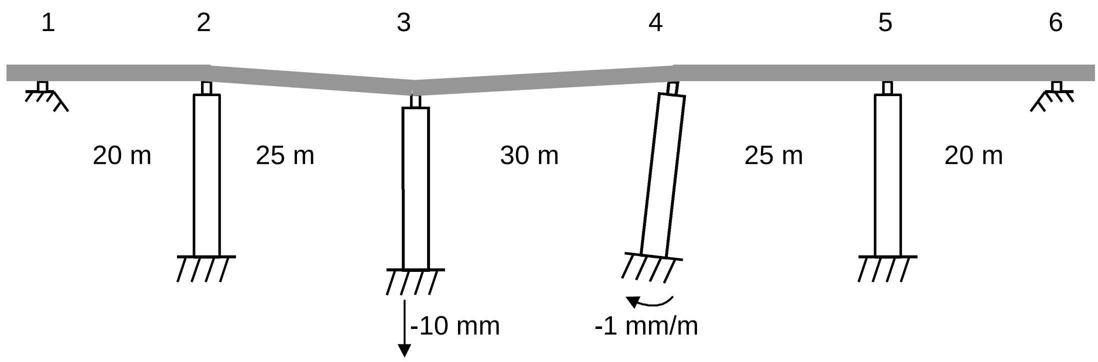

Figure 4: numerical example
displacements: $\Delta H_{2,2}$ = -10 mm, $\Delta H_{3,1}$ = 10 mm, $\Delta H_{3,2}$ = 40 mm, $\Delta H_{4,1}$ = -10 mm, $\Delta H_{5,1}$ = -25 mm

According to the ISO-guide [7] an estimation of uncertainty in final results has to take all relevant sources of errors and their possible correlations into account.

One kind of correlation is due to the influences b) through e); the two laser beams leaving module number n are rotated in the same sense and by the same angle. The corresponding displacements $\Delta H_{n-1,2}$ and $\Delta H_{n+1,1}$ have the same effect as a true inclination of pier n. As a consequence these influences contribute in full height to the uncertainty of inclination results. On the other hand their influence on settlement is just as low as that of true pier inclination.

The uncertainties of two sensors, which belong to the same module and hence share a common housing as well as a common power supply, may be – at least partly - correlated. Since little is known about the degree of correlation, only the extreme cases are taken into consideration. With regard to the complexity of equations 1 through 4 an analytical solution, as described in the guide, would require an unreasonable effort. Consequently the numerical approach proposed in [8] was preferred to an analytical one. The graph in figure 5 shows the uncertainty of calculated settlement as a function of point number and degree of correlation. For uncorrelated input signals (correlation factor r = 0) the resulting uncertainty near the center of the bridge is less than twice the uncertainty of the input

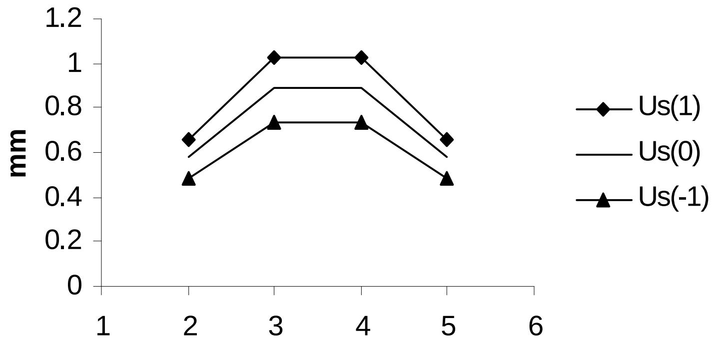

Figure 5: standard uncertainty of calculated settlement at different piers for different correlation factors r = 0, r = 1, r = -1

variables, slightly decreasing towards the ends. The marked lines give the uncertainties for 100%-correlation with equal and opposite signs (r = 1 and r = -1). Since these extreme cases differ only slightly from the uncorrelated case, more precise determination of correlation factors is not necessary.

4 CONCLUSION

Tests were carried out with a prototype system in the laboratory under simulated field conditions confirming the suitability of the new concept for long-term on-site monitoring. Its benefits for the field of application concern multiple output information, ease of adjustment and maintenance, stable sensitivity, fast response and moderate cost.

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