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Wave-Shaped Wire Extensometer for Linear Displacement Measurement

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Abstract.. This article presents the concept and the method of operation of an innovative device for the measurement of relative displacements, and a study of its metrological properties. The mechanical system of the proposed measuring instrument is similar to the systems of existing wire displacement transducers. The construction of previously known devices for measuring relative displacements containing a measuring wire (wire strain gauges, wire dilatometers) involves direct attachment of the wire to the anchors of the device, through either additional elastic elements or mechanical transmissions. In this measuring instrument, the elastic sensor element has been replaced with a wavy wire which is attached directly to the anchors of the device. The measuring range of this device is four times as large as that of a wire displacement transducer with a measuring base of the same length. The increased measuring range will enable the use of this equipment for measuring relative displacements of building elements in the range 2–3 mm, with a measurement uncertainty of 0.025%.

Key words: extensometer, metrology, strain gauges

1. INTRODUCTION

Vibrating wire displacement transducers have been employed for several decades to measure deformations in various types of structures and landforms [1]. Their longstanding use is primarily due to their advantageous features, such as their excellent stability of metrological parameters over extended periods, which ensures consistent and reliable measurements, as well as their high reliability and robustness in diverse environmental conditions [2].

In the context of landslide monitoring, extensometers are frequently used to record ground surface or structural element displacements [3]. Extensometers provide precise measurements of movement over defined distances, allowing for early detection of instability. Complementing these, strain gauges are often emplyed to monitor fissures and cracks forming within structures or geological formations. Similar measurement techniques are also applied in the field of rock mechanics, where they are used to observe displacements and deformations within rock masses, aiding in the prediction of potential failures or seismic events [4].

Mining activities significantly influence the surrounding environment, often causing surface subsidence - the gradual sinking of land above excavated areas. This phenomenon results from underground mining operations that remove large volumes of material, leading to a loss of support for the overlying strata [5]. Monitoring these surface movements is essential for assessing environmental impact and ensuring safety. Typically, geodetic methods, such as leveling and total station measurements, along with satellite-based techniques like InSAR (Interferometric Synthetic Aperture Radar), are employed to track surface deformations with high precision [6].

In existing strain gauges for measuring relative displacements, the wire is attached to the device's anchors directly or through additional intermediary elements [7]. The measuring base of the device is the distance between the anchors. In devices where the wire is attached directly to the anchors, it is located inside the casing, and its clamps are mounted on the anchors. Such a design results in an instrument with a relatively small measuring range, due to the elastic properties of the wire. To obtain correct vibrations of the wire, its tension and consequently its deformation must be higher than a certain minimum value. However, the maximum tension in the wire cannot exceed its tensile strength. In practice, maximum stresses are often lower due to relaxation phenomena. The deformation range of a transducer wire is approximately 2 mm per meter; therefore, a transducer with a measuring base of 100 mm has a measuring range of about 0.2 mm. A transducer of this type is shown in Figure 1. Due to the small measuring range, the applicability of this type of device is limited to the measurement of linear displacements (deformations) in solid structures.

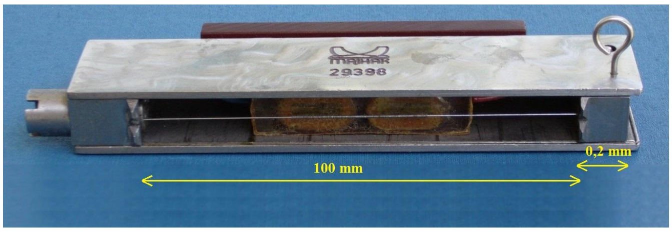

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Fig. 1 Maihak strain gauge – measuring base 100 mm, range 0.2 mm.

In the case of relative displacement measurements within gaps caused by the loss of construction continuity (cracks) this range is insufficient. Traditionally, range was increased using auxiliary springs or levers, which added complexity and reduced accuracy. The proposed solution eliminates these drawbacks. A diagram of this type of device is shown in Figure 2. In the construction, one clamp of the wire is attached directly to one of the device's anchors, and the other clamp is connected to one end of the spring. The other end of the spring is attached to the opposite anchor of the device. This solution complicates the mechanical system of the displacement transducer, which significantly limits its possible applications.

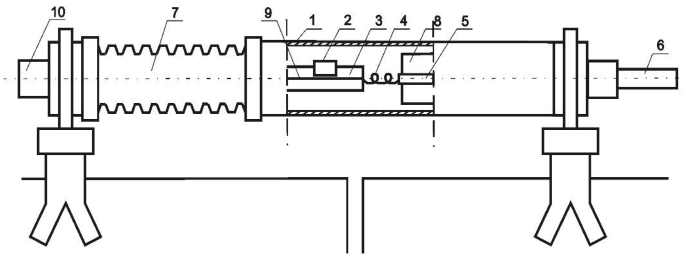

Fig. 2 Strain gauge: 1 – casing, 2 – electromagnetic transducer, 3 hh– elastic element, 4 – measuring spring, 5 – mandrel, 6 – cable, 7 – rubber cover, 8 – guide sleeves, 9 – wire, 10 – touch tip.

To increase the measuring range of the displacement transducer, a mechanical transmission—for example in the form of a lever—may also be used, as shown in Figure 3. This type of extensometer is rarely used due to several limitations, including potential inaccuracies introduced by the mechanical linkage and the added complexity of calibration. Despite these drawbacks, such an instrument offers certain advantages, such as the ability to measure larger displacements that would otherwise exceed the capacity of the basic transducer. This approach effectively amplifies small displacements, making them measurable by the sensor.

Such an instrument has been constructed and used at the Strata Mechanics Research Institute of the Polish Academy of Sciences in Cracow, where it was applied in specialized experiments requiring extended measurement ranges. The design typically involves a lever mechanism that translates the displacement of the specimen into a proportional movement at the sensor's sensing element, thus enabling more precise measurement over a broader scope. However, careful consideration must be given to the calibration process to ensure accuracy, as the mechanical transmission can introduce errors due to factors like friction, backlash, or deformation of the lever components. Overall, while the use of mechanical transmissions like levers can be beneficial in specific applications, modern displacement measurement often favors electronic or optical methods that provide higher accuracy and reliability without the complexities associated with mechanical linkages.

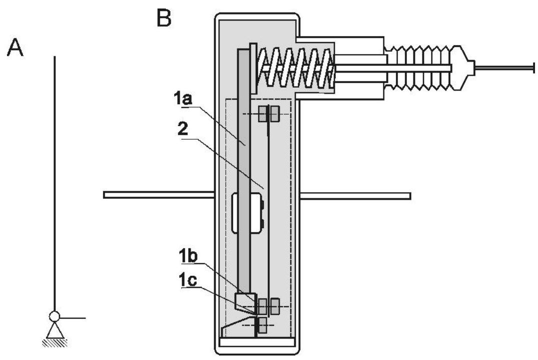

Fig. 3 A - lever system; B - lever extensometer scheme, 1a - longer lever arm, 1b - shorter lever arm, 1c - lever rotation axis, 2 - wire.

To extend the measuring range of the wire in the transducer, various mechanical systems are used, which increase the device's complexity and may compromise its metrological properties. Often, simple and low-cost instruments can still yield valuable measurement results [8][9].

The aim of this study is to present an innovative extensometer with a wave-shaped wire, offering a fourfold increase in measurement range compared to conventional devices.

One of the most important advantages of this device for measuring linear displacements is a solution that allows energy from the tested object to be converted into an output signal. The signal is independent of the apparatus attached to the extensometer. Also, this signal does not degrade during transmission through unshielded cable, as is the case with inductive, electroresistant and photoelectric strain gauges, which are subject to interference.

The disadvantage of this type of device is the effect of flow in long-term studies. Knowing the flow characteristics, one can take into account the error in the measurement instrument that results from this phenomenon. It is also possible to use an additional reference device, suitably blocked and installed under the same conditions as the measuring instruments, to take account of errors resulting from the flow.

2. METODOLOGY

In the proposed device, the sensor wire element is attached directly to the anchors. A similar solution is used in the construction of strain gauges used for measuring concrete mass strain. To increase the measuring range, it is proposed to replace the straight measuring wire with a wave-shaped wire. A diagram of the apparatus is shown in Fig. 4.

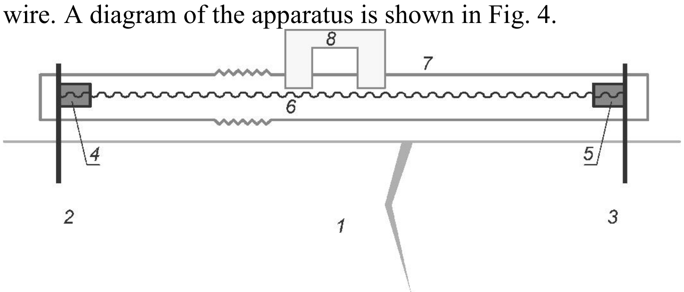

Fig. 4 Diagram of the relative displacement measuring device: 1 – construction with an expansion joint or crack, 2,3 – anchors, 4,5 – wire clamps, 6 – wave-shaped wire, 7 – casing, 8 – electromagnet.

The device consists of a sensor elastic element, clamps, and an electromagnet. The sensor element is made from a piece of 0.5 mm diameter piano wire, bent into a sinusoidal shape with a wavelength of 15 mm and an amplitude of about 1 mm, using specialist precision bending tools. This process was carried out under controlled conditions, and the bent wire was then heat treated in a hardening furnace at 200 ºC for 1 hour, then slowly cooled in a protective atmosphere, which ensured the stability of the mechanical properties and the flexibility of the element. Such wire is more flexible than straight wire. This increases the measuring range of the instrument by more than four times compared to an instrument containing a straight wire of the same dimensions.

The piano wire is ferromagnetic, which makes it possible to excite vibrations in it and convert them into an electric signal magnetically. For this purpose an electromagnet is used. Its pole shoes are very close (less than 1 mm) to the wire. At the start of the measurement process an exciting electric pulse is applied to the electromagnet terminals, causing vibrations in the wire. The optimum amplitude of the pulse is 100 V, and its duration is about half of the wire vibration period. After excitation, the electromagnet converts the mechanical vibrations of the wire into an electric signal of sinusoidal decaying type. The special electronic transducer [10] attached to the instrument measures the vibration period of the signal, installed with a frequency which ensures higher measuring accuracy. The transducer, after generating the exciting pulse, measures the duration of 200 periods of the input signal, i.e. 200 periods of vibration of the wire. The resolution of this measurement is 2 microseconds. This means that the resolution of the measurement of a single period is 10 microseconds. The meter is stabilized by a precise quartz oscillator, so that its measurement error (the three-year stability is about 10^{-6}) is far less than the measurement error of the extensometer and can be neglected.

Mounting the measuring element involved securing the wire ends in special clamps that were precisely positioned and secured on anchors, ensuring repeatability and minimizing internal stresses. One of the clamps is glued in the case tube, close to one of its ends. The other clamp is glued in an additional short piece of tube sliding inside the case at its opposite end. Thus, the instrument is stiff perpendicularly to its axis and elastic along it. The measuring device is mounted by inserting the anchors into holes glued in the structure with cracks or expansion joints. The device was calibrated by comparing the readings with a standard extensometer, under controlled conditions to minimize the influence of external factors.

3. TESTING OF METROLOGICAL PROPERTIES

The properties of a wave-shaped wire as a mechanical oscillator are certainly different from the properties of a tightened wire, because, for example, its longitudinal stiffness is smaller than its transverse stiffness. Therefore, before using the extensometer, its metrological properties should be examined. For this purpose, two laboratory tests were carried out on the new equipment.

To test the metrological properties of the constructed extensometer, it was installed on a test stand (Fig. 6), which enables the precise adjustment of displacements of one of the anchors of the tested device in the range 0–2 mm, under conditions of stable ambient temperature. The displacement is effected by a screw and controlled by two clock displacement sensors. The error of the sensors was checked using gauge blocks with a step of 0.01 mm, and was found to be less than 0.001 mm. The true displacement was calculated as the mean of two readings. This method ensures the determination of displacement at an accuracy better than 0.1%, which is sufficient for testing an extensometer.

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As part of the comprehensive analysis of the metrological properties, the researcher focused on identifying the optimal placement of the electromagnet in relation to the elastic sensor element, which in this case is a wave-shaped wire. This step was crucial to ensure accurate and reliable measurements, as the positioning of the electromagnet directly influences the strength and uniformity of the magnetic field interacting with the sensor. To achieve this, a series of systematic experiments were conducted, during which the electromagnet was gradually moved along different positions relative to the elastic element while monitoring the sensor's response. The data collected were then plotted to visualize the relationship between the electromagnet's position and the sensor's output. The resulting graph, shown in Figure 5, illustrates the variations in measurement accuracy or sensitivity depending on the electromagnet's placement. From this graph, the position corresponding to the maximum response or optimal signal-to-noise ratio was identified, indicating the most advantageous location for the electromagnet to be situated during practical applications. This optimized positioning helps enhance the overall performance of the measurement system, ensuring consistent and precise readings in subsequent experiments and potential real-world deployments.

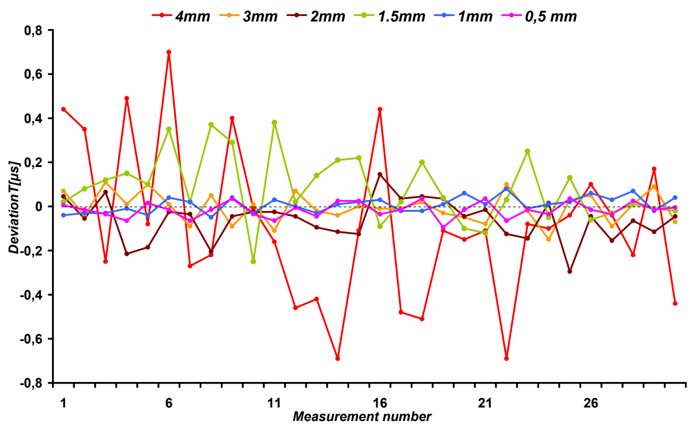
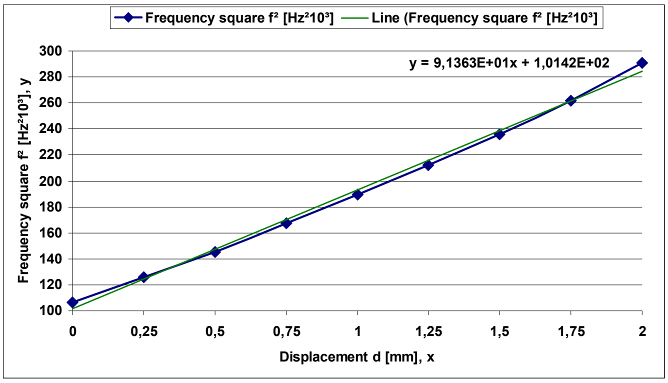


Fig. 5 Graph of deviation as a function of the position of the electromagnet on the elastic sensor element.

The results of the experiments clearly demonstrate that the optimal placement of the electromagnet in relation to the wave-shaped wire lies within a distance range of approximately 0.5 to 1 mm. This specific interval was identified because it produced the smallest deviation, indicating the highest accuracy and stability in the measurement system. Precise positioning within this range ensures that the electromagnetic influence on the wire is maximized while minimizing potential sources of error, thereby enhancing the overall reliability of the transducer.

Figures 6a, 6b further illustrate these findings by presenting detailed graphs that depict the relationship between the square of the frequency and the displacement of one of the instrument's anchors relative to the other. These graphs highlight the predictable nature of the transducer's response, showing that as the squared frequency increases, the displacement follows a more or less linear trend [11]. This linear dependence is similar to what is observed with strain gauges, where the output signal correlates proportionally with the applied strain. Such a relationship not only simplifies the interpretation of the measurement data but also confirms the consistency and repeatability of the transducer's behavior across the tested range. Overall, these insights contribute to a deeper understanding of the device's operational characteristics and pave the way for further optimization and application in precision measurement tasks.



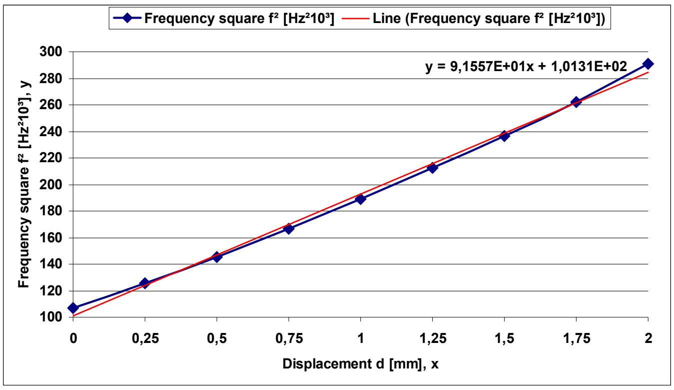
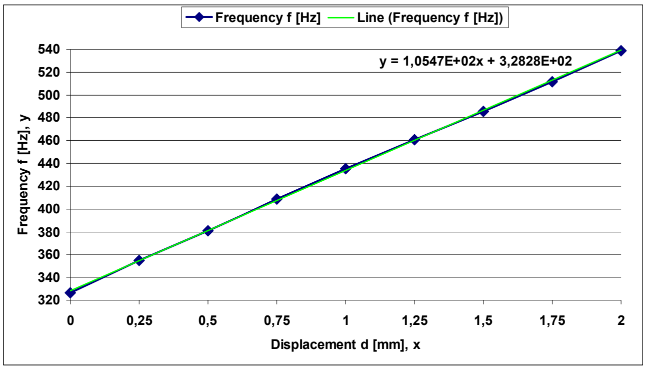


Fig. 6a, 6b Graph of squared frequency against displacement for the first test and the second test.

The observations indicate that the traditional theoretical formula (1), which suggests a linear relationship between wire tension and the square of the vibration frequency, does not accurately describe the behavior of a wave-shaped wire. Experimental results demonstrate that the properties of a straight wire and a wave-shaped wire differ significantly.

Notably, the data from Figures 6a, 6b reveal that the frequency's dependence on displacement exhibits a more linear characteristic. Consequently, it is reasonable to consider the frequency's dependence on displacement as a relevant factor for this type of device, suggesting that models should be adapted to account for the unique properties introduced by the wave-shaped configuration.



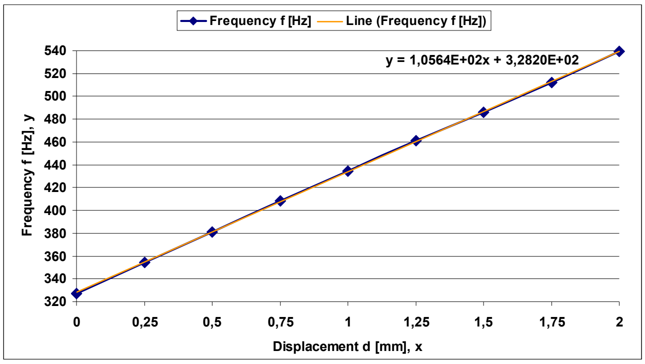


Fig. 7a, 7b Graph of frequency against displacement for the first and second test.

Based on the results presented in Figures 7a, 7b the good stability of the characteristic of the device was confirmed. In further considerations, an averaged characteristic was assumed:

$$f(x) = 105.56 \cdot \Delta x + 328.24 \tag{1}$$

f - frequency

x - displacement

Δx - displacement change

The deviation of measurement results from the characteristic never exceeds 1.7 Hz. On this basis, the nonlinearity error of the device was determined as being within a range of 0.8%. For every value of displacement, the frequency was measured 20 times. Standard deviations were calculated for all of the results. The worst case occurred for a displacement of 0.5 mm. On this basis, the uncertainty of measurement, for an expansion factor of 3, was determined to be in the range ±0.04%. The measurement system consisting of the extensometer and the readout system described in section 2 achieves a very high resolution of measurement, with a value of 0.02 micrometers.

The extensometer was also tested at temperatures ranging from 3 to 31 ºC. For the test it was fixed to a solid steel bar with thermal coefficient 12 ppm/K. The same value is often assumed as the thermal coefficient of concrete. The thermal characteristic is shown in Figure 8. For the above temperature range, the thermal coefficient of the extensometer is 0.0624 Hz/K. The thermal error for the whole range (3 to 31 ºC) is determined as 0.8%. For non-extreme temperatures, or for rough measurements, the influence of temperature on the measurement results can be neglected.

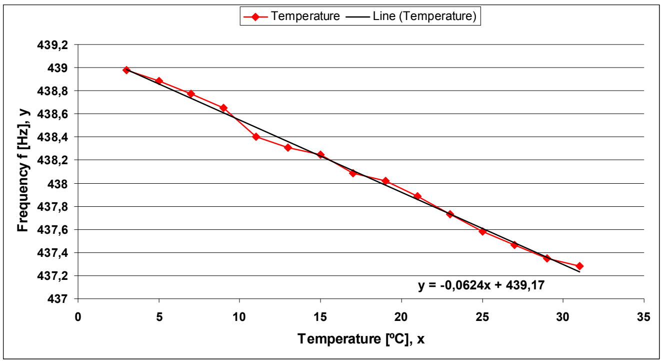


Fig. 8 Graph showing the dependence of frequency [Hz] on temperature [ºC].

All of the above tests were performed in laboratory conditions over a time span of several hours, ensuring controlled and repeatable measurements. The wave-shaped wire used in the extensometer is subjected to a continuous tension, which, given the properties of the material (piano wire) inevitably leads to creep phenomena. Creep, defined as the slow, time-dependent deformation under constant load, can cause significant measurement errors in the instrument if not properly characterized. Since the accuracy of the extensometer depends heavily on the stability of its components, understanding and compensating for creep effects is essential for precise long-term measurements.

To accurately assess the extent of creep-induced errors, a dedicated testing procedure was implemented. The wire was tensioned with a force equivalent to 40% of the instrument's maximum measuring range, a level chosen to simulate typical operational conditions while ensuring the stress remained within material limits. The tension was maintained continuously over a prolonged period—exceeding two months—to capture the full scope of creep behavior, including both short-term and long-term effects. Throughout this period, the deformation of the wire was monitored meticulously at regular intervals, allowing for detailed analysis of how the material's strain evolved over time under constant load.

The results of this extended testing are summarized in Figure 9, which illustrates the temporal progression of creep deformation. Initially, a relatively rapid increase in strain is observed, characteristic of primary creep, followed by a more gradual, steady deformation phase representing secondary creep. The data indicates that even after several weeks, the creep process does not fully stabilize, suggesting that the material continues to deform slowly over time. These findings highlight the importance of incorporating creep compensation mechanisms within the extensometer design or calibration procedures to ensure measurement accuracy over extended periods. Moreover, understanding the creep characteristics allows for more precise correction factors to be applied in practical applications, thereby improving the reliability of the instrument in long-term monitoring scenarios.

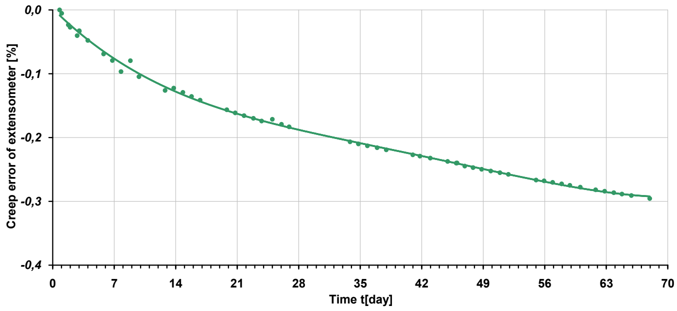


Fig. 9 Creep error of the extensometer over two months.

The creep error becomes linearized over time, meaning that as the testing period extends, the rate of creep error stabilizes and can be approximated by a straight-line trend. For example, during the last two-week period of the test, the error has been estimated at approximately 0.8% per year, indicating a relatively steady and predictable rate of deformation. This linearization allows engineers and researchers to better predict long-term behavior and assess the durability of materials or structures under sustained load conditions. Understanding this trend is crucial for designing components that must maintain integrity over extended periods, as it provides a reliable basis for estimating cumulative deformation and potential failure risks over the service life of the material or structure.

4. APPLICATION OF PROTOTYPE EXTENSOMETER

To measure the width of a wall crack, a prototype extensometer was employed, as shown in Figure 10. This device was specifically designed to provide precise readings of crack opening displacements over time, which is essential for understanding the crack's development and potential impact on the structural integrity. In addition to the extensometer, a clock displacement sensor was installed to serve as a comparative measurement tool. The purpose of using two different instruments was to verify the consistency of the measurements and to gain a more comprehensive understanding of the crack behavior.

It is important to note that, from a technical standpoint, it was not feasible to install both devices at exactly the same location on the wall. Due to physical constraints and the need to avoid interference between the instruments, each sensor was placed slightly apart. As a result, the measurements obtained from the extensometer and the clock displacement sensor can only be considered approximate comparisons, since slight differences in their positions may lead to variations in the recorded data. Despite this limitation, the results from both devices showed a similar overall trend, indicating that they are both effectively capturing the crack's behavior.

This consistency between the two measurement methods provides confidence in the reliability of the data and suggests that the observed crack movements are accurately reflected by both sensors. Using multiple measurement techniques not only helps validate the results but also offers a more robust understanding of the structural response. Overall, this approach highlights the importance of employing different tools to monitor structural changes, especially when precise and reliable data are critical for assessing safety and planning maintenance or repairs.

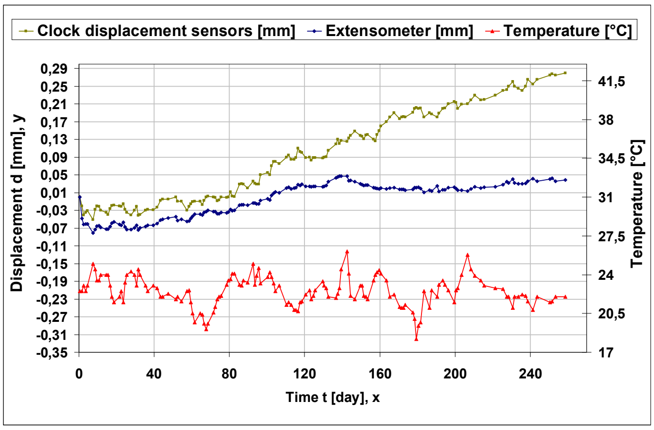


Fig. 10 Graph showing changes in the crack width.

5. FUTURE DEVELOPMENT AND RESEARCH DIRECTIONS

In light of the results obtained, there are many potential directions for development and further research that can further enhance the functionality and applications of this innovative transducer. Below are some key areas worth noting:

Miniaturization and system integration
The development of miniature versions of the device will allow its use in even more limited spaces, e.g. in monitoring small structural elements or in hard-to-reach places. Integration with wireless data transmission modules will enable remote reading of results, which is particularly important in difficult terrain conditions or in large facilities.

Automation
Implementation of the device in a system that will allow for automatic collection, analysis and visualization of data in real time. This solution will increase the effectiveness of monitoring, enable early detection of irregularities and rapid response to threats, e.g. in the case of landslides or structural damage.

Long-term stability and resilience studies.

6. SUMMARY AND CONCLUSIONS

This article introduces an innovative displacement measurement device that utilizes a wave-shaped wire as its elastic element, offering significant advantages over traditional strain gauges. This is the first application of a wave-shaped wire as an oscillating element in precision displacement measurement. The primary focus is on developing a simple, cost-effective, and highly accurate instrument capable of measuring relative displacements with an extended range. The key innovation of the proposed device lies in replacing the conventional straight wire with a wave-shaped wire, which increases the measurement range by more than four times without adding mechanical complexity. This design enables effective monitoring of displacements in structures such as buildings and geological formations, particularly in scenarios involving cracks or ground movements caused by underground mining or landslides.

The mechanical system of this transducer is similar to existing wire displacement transducers, but the unique wave-shaped wire enhances its elastic properties, allowing it to detect larger displacements (up to 2–3 mm) with a measurement uncertainty of only 0.025%. The device operates by exciting vibrations in the ferromagnetic wave-shaped wire using an electromagnet, then measuring the vibration period to determine displacement. Laboratory tests confirmed the device's high resolution (up to 0.02 micrometers), stability, and reliability under various conditions, including temperature variations and long-term creep effects.

Metrological evaluations demonstrated that the relationship between vibration frequency and displacement is sufficiently linear for accurate measurements, with an error margin within 0.8%. The long-term creep behavior was characterized over two months, revealing a predictable, linear trend that can be compensated for in practical applications. The device also showed resilience to temperature changes within the tested range, with minimal impact on measurement accuracy.

Potential applications of this transducer are broad and include monitoring structural cracks, landslide displacements, and geological movements caused by mining activities. Its simple construction, combined with high accuracy and an extended measurement range, makes it suitable for long-term structural health monitoring - especially in environments where traditional sensors may face limitations due to mechanical complexity or interference.

Future work includes plans to expand the extensometer's functionality by enabling communication with IoT systems, enabling its integration with SHM platforms and the use of AI algorithms for automatic anomaly detection and structural behavior prediction. Integrating these technologies will significantly expand the device's potential for modern, automated infrastructure monitoring.

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