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# Measurements of rope elongation or deflection in impact destructive testing

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A B S T R A C T

The computation of energy dissipation in mechanical protective systems and the corresponding determination of their safe use in mine shafts, requires a precise description of their bending and elongation, for instance, in conditions of dynamic, transverse loading induced by the falling of mass. The task aimed to apply a fast parallactic rangefinder and then to mount it on a test stand, which is an original development of the Central Mining Institute's Laboratory of Rope Testing in Katowice. In the solution presented in this paper, the measuring method and equipment in which the parallactic laser rangefinder, provided with a fast converter and recording system, ensures non-contact measurement of elongation, deflection or deformation of the sample (construction) during impact loading. The structure of the unit, and metrological parameters are also presented. Additionally, the method of calibration and examples of the application in the impact tests of steel wire ropes are presented. The measurement data obtained will provide a basis for analysis, the prediction of the energy of events and for applying the necessary means to maintain explosion-proofness in the case of destructive damage to mechanical elements in the mine atmosphere. What makes these measurements novel is the application of a fast and accurate laser rangefinder to the non-contact measurement of crucial impact parameters of dynamic events that result in the destruction of the sample. In addition, the method introduces a laser scanning vibrometer with the aim of evaluating the parameters of the samples before and after destruction.

## 1. Introduction

The calculation of energy dissipation in the mechanical protection system made from stretched ropes, composing the artificial bottom of the shaft, requires precise measurement of bending and extending of the rope during the fall of dynamic load weight. The computation of energy dissipation in the mechanical systems, which are for instance made from austenitic steel (Akai, Shiozawa, Sakagami, Otobe, & Inaba, 2012), including the application of novel measuring technologies, such as thermovision and lasers (La Rosa & Risitano, 2000; Lipski & Mroziński, 2008; Pieczyska, 1999), can be found in the methodology of testing of monotonic or cyclic tensioning of steel samples. Designing steel protective systems, and consequently creating the framework for their safe use in the shaft and other mine workings, requires a precise description of the bend and elongation, e.g. of the rope, in the course of dynamic, transverse or longitudinal loading with falling mass. These are the tests that determine the capability

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of the material for transmitting sudden impact loads. The most frequently applied impact tests are the impact bending test and the impact elongation test.

Impact tests are carried out with the aim of assessing the behaviour of the material in conditions that give rise to the brittle cracking produced in the sample by a high rate of deformation, due to the dynamic action of force and temperature.

When testing the impact resistance of steel wire ropes, the parameter of dynamic elongation in the time up to the moment of breaking is of particular importance. The short amount of time and a high amplitude acceleration energy require a device that will reliably measure these parameters as a function of the force acting at the time.

For the purposes of such measurements, the Central Mining Institute's Laboratory of Laser Technology (in Katowice) has developed a measuring unit which makes use of a fast parallactic rangefinder. The principal issues were its metrological parameters (including signal recording and analysis) and, also, its size and resistance to electromagnetic and mechanical interference. This resulted in the rangefinder being contained in purpose-designed casing and holders. After the laboratory calibration testing was completed, initially in the accredited Laboratory of Technical Acoustics, the whole measuring system was installed in the testing stand of the institute's Rope Testing Laboratory.

The ropes used in the tests were composed of a core wire which had one layer of round wires wound around it. Such ropes (called single-lay) are characterized by small elongation and high stiffness. Their main technological parameters are their angle of lay, multiplicity of pitch, and coefficient of lay. Constructional and technological parameters are strictly interrelated and they determine the final characteristics of the rope. The ropes are generally produced from carbon steel, with a carbon content in the range of 0.33–0.98%. The requirements for round wires intended for the production of strand ropes are included in the standard PN-ISO 6984. The material for the wire is smelted in an OH furnace or electric furnace, by using a basic oxygen process or an equivalent method. The ready-made wire must not have either surface or internal defects that may adversely affect its use. In cases where this has not been specified, the wires must be zinc covered. The zinc applied must have a cleanness of 99.9%. Steel with other chemical compositions with enhanced corrosion resistance are currently only applied in a small scale. Their composition depends on the ropes application and its working conditions, typically, being chromium–nickel steel with a low carbon content ($C = 0.12\%$). For high-strength wires, high-carbon steel is used, with a carbon content not lower than 0.75%.

The most popular ropes are those produced from 6 round strands helically wound around the core. The strands may contain 1–4 wire layers, in the case of the single wire ropes tested.

## 2. Methods

### 2.1. *Mechanical strength testing methods*

The static experimental testing of real rope-breaking force is conducted in full on the testing machine, calibrated to class I accuracy, of WPM-Leipzig, with a measurement range of 0–5000 kN. This machine has a horizontal layout and a manual-control hydraulic drive.

The rope section being tested is fastened in the holders of the testing machine, and then loaded starting from an initial force of $P_0$ up to breaking point. Simultaneously, the elongation of the rope and the rise of the load are measured. The test is assumed to be completed when the break of a strand occurs, so in this case, the breaking of only one wire. The procedure is applicable to steel ropes with a diameter of up to 70 mm.

Dynamic loads differ from static loads. The resistance and reaction load are different (Siemieniec et al., 2002). Tests conducted in the Central Mining Institute, e. g on rock bolts at impact loads, have confirmed the difference between mechanical strength parameters, determined on their basis, and parameters determined in static tests (Pytlik, 2002). As an example, the energy that is needed for the penetration of laminate in dynamic conditions can be several times higher than that for static penetration (Barcikowski, 2012).

The impact phenomena may differ depending on the value of velocity, energy and mass of the impactor, mass of the target, geometrical characteristics, such as shapes of the bodies taking part in the process, or the direction of the velocity vector relative to principal directions in the sample. Here, the impact velocity is of particular importance (Zukas, 1990).

The GIG Laboratory for Testing Mechanical Equipment has a testing stand in which the impact mass falls from a given height on to a cross bar that preliminarily loads the ropes being tested, in two variants of fastening (Fig. 1). One is used for the impact test of transverse loads, and the other for longitudinal loads. The design of the testing stand also imposed a method for mounting a rangefinder. It was assumed that the laser sensor would be installed on fixed base elements of the machine, either under or over the cross bar. Variants of the measuring sections (red arrows) are shown in Fig. 1.

The method relies on a single impact by dynamic force produced by the mass falling on the initially loaded rope mounted in the test stand, with a simultaneous measurement of load, displacement and time up to the moment of breakage. The *Spider 8* recorder was used with a HBM measuring amplifier (DMCplus) and provided with A/D converters (HBM Operation Manual, 2002) to which force sensors and a laser displacement sensor were connected.

The test stand with construction elements for impact tests of transverse and longitudinal loads of steel wire ropes and the same configuration as in Fig. 1 can be seen in Fig. 2.

The deformation measurements of mechanical elements in impact destructive testing were performed for ropes composed of 6 round strands which are wound helically around the core.

Steel wire ropes and other flexible connectors are not able to resist bending, nor are they able to transfer compressive loads. Tensile forces, and consequently stresses existing in the ropes (flexible connectors), fastened in two points should be calculated according to the formulas of theoretical mechanics, taking into account the form of sag as the chain curves.

Impact phenomenon is produced through the contact of at least two bodies which have different velocities. The forces which occur during this contact are called instantaneous. They act in a very short time and reach very high values. They

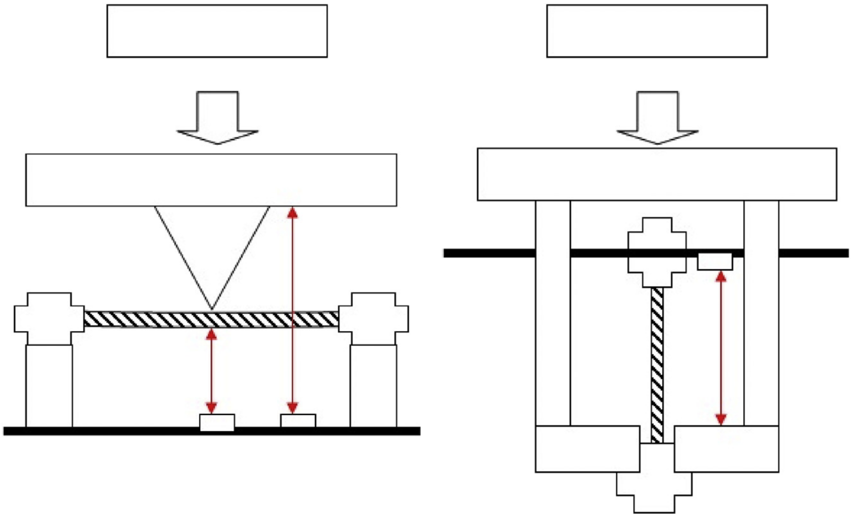

**Fig. 1 – Configurations of impact measurements.**

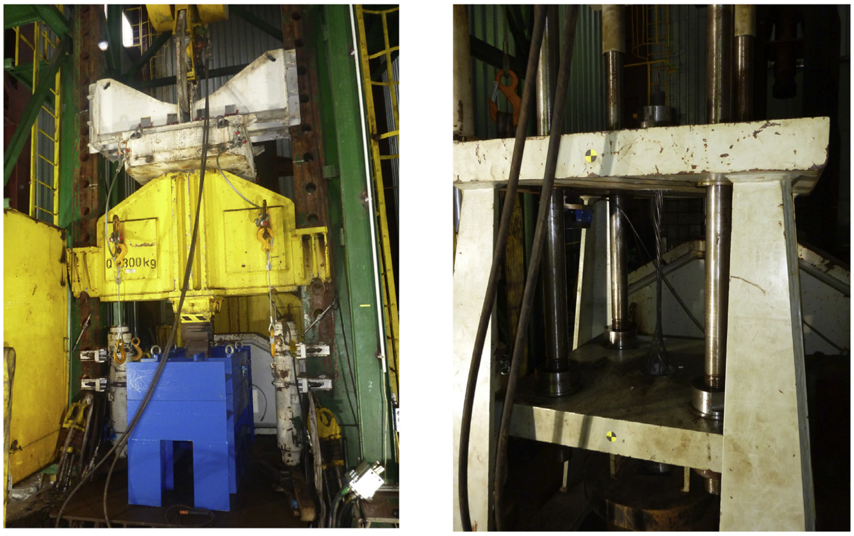

**Fig. 2 – View of testing stand with construction elements for impact tests of transverse and longitudinal loads of steel wire ropes.**

lead to the breaking of the flexible connector or its overloading. The dynamic behaviour of construction using such elements resulting from external loading is a very complex issue (Pałkowski, 1994). The principal dynamic characteristics of these constructions are:

- Maximum deflection of a flexible connector,
- Maximum instantaneous normal stress in a single connector, and in the whole construction,
- Frequency (periods) of free vibration,
- Damping properties,
- Type of dynamic (forcing) loading.

The course of testing can be divided in to three phases:

Phase I – loading of the rope sample with constant static force of the value $Q_o = m_2$ g producing deflection ($f_o$),

Phase II – free fall of impact mass $m_1$ on to the cross bar and the production of impact load in a very short time period $\Delta t$,

Phase III – the sticking of masses together ($m_1 + m_2$), such a system together with ponderable rope makes either transverse or longitudinal vibration, with different frequencies $\omega$.

From earlier investigations (Hankus, 2000) it follows that due to friction resistance which exists in the rope, higher frequency vibrations are strongly damped and may be omitted.

Upon collision of the bodies, their velocities must be equalized. Provided that the colliding bodies are ideally stiff, this equalization must take place in an incredibly short amount of time and acceleration, and consequently, infinite force must appear. Owing to the deformation of the bodies the time of impact and distance are very short. Steel wire ropes, due to their complicated structure, reveal elastic-plastic properties, which means that after impact the deformation vanishes partially, but some durable deformation remains. In the course of gradually increasing loading, a recording was conducted of the values of the dynamic force $P_{di}$, and elongation of the sample $\Delta S_i$.

The value of force F of the dynamic impact of mass on the rope tested was measured using an extensometer placed under the nut screwed on to the rope clamp. The values of force and elongation were recorded as function of time t with the sampling frequency $fp = 2400$ Hz. The number of measurements, per channel, was 7200.

### 2.2. *Laser-based method of deformation measurement*

The task of the laser rangefinder mounted on the impact testing stand, is the realization of static (phase I – order sample rope for constant force static) and dynamic measurement (phase II and phase III) of the deflection/elongation rope in a very short time and with the possibility of transverse or longitudinal vibrations damped by different frequencies.

#### 2.2.1. *Construction of laser device – the idea*

The schematic diagram of the device is shown in Fig. 3. The measurement and recording of force (accelerometer and extensometer dynamometers) and measurement of bending/elongation are performed at the same system time by the digital recorder. The compatibility of data is also ensured by current-voltage converters and a common A/D measuring card.

In dynamic measurements of deformation or distance (mine shafts, buildings, road acoustic barriers), the CMI laser Technology Laboratory has successfully applied laser-based displacement sensors (Białożyt et al., 2008; Passia, Kompała, & Szade, 2012).

Success is conditioned by matching the parameters of all units in measurements of wide-range events (force, displacement), in very short time ranges (ms, s).

#### 2.2.2. *Characteristics of the elements of the displacement measurement line*

*The FT 80 RLA* is the optical sensor designed to perform contactless measurement of distance (Distance Sensors SensoPart, 2014). It is characterized by:

- a measuring range: 250–750 mm;
- a reaction time: 0.4 ms;
- 0.1% resolution of maxima measuring range;
- 2 digital outputs;
- an analog output signal of 4 … 20 mA;
- sensor signalling functions;
- size: 25 × 83 × 65 mm (H × W × D).

The FT80RLA sensor also has an averaging function which leads to “smoothing” of the shape of function. Therefore, the shape of the output signal can be adjusted to the application required. The averaging function relies on the idea that the measuring value is entered into FIFO memory, in the 100 position register. Every new value that appears shifts the recorded values back by one position, with the first being erased. Depending on the settings, the average is determined based on 10 or 100 values measured. As a consequence, the analog signal can be shaped through the selection of the averaging value, which increases the reliability of the distance measurement of, for example, rough surfaces. The sensor reaction time is 0.4 ms, with averaging switched off, or4 ms /40 ms with the averaging function on. The rangefinder applies a 650 nm (red) laser beam; a class 2 laser (EN 60825/1). Power supply: 24 VDC, transmission of data through interface RS 485, protection of casing IP 67.

The I/U converter (integrated circuit) is an important element of the measuring line. The schematic diagram is shown in Fig. 4.

## 3. Results and discussion

### 3.1. *Laboratory tests of measuring characteristics*

The applicability tests of the rangefinder in measuring low-frequency dynamic phenomena were carried out in the CMI Laboratory of Technical Acoustics. The PCA-accredited procedure and method are based on the ISO 16 063-41:2011 standard. The offsets were performed with a block (30 cm) and placed on the vibration table APS-113 Electro-Seis (0.5–100 Hz) (APS-113 Electro-Seis, 2014), as in Fig. 5. Force parameters were sinusoidal vibrations with an amplitude pp

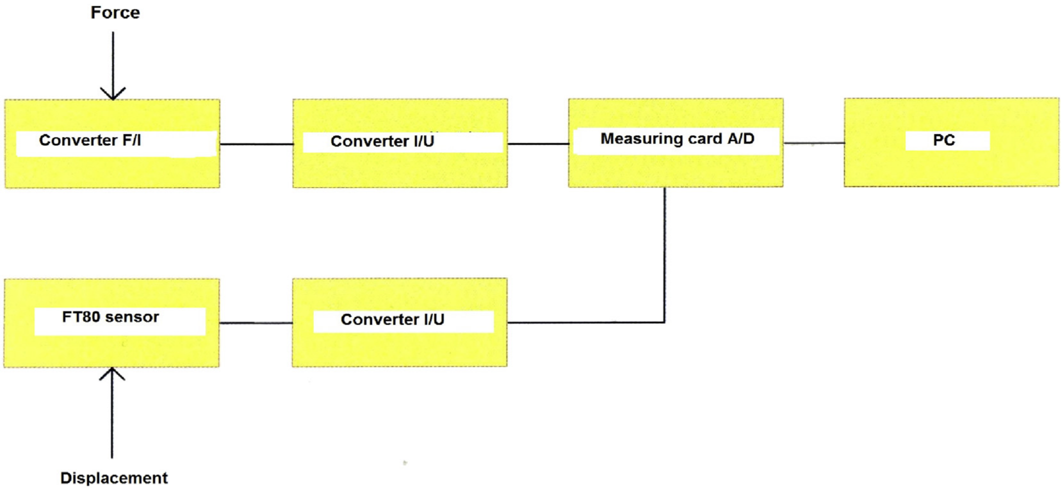

**Fig. 3 – Schematic diagram of measuring system with an FT80 rangefinder.**

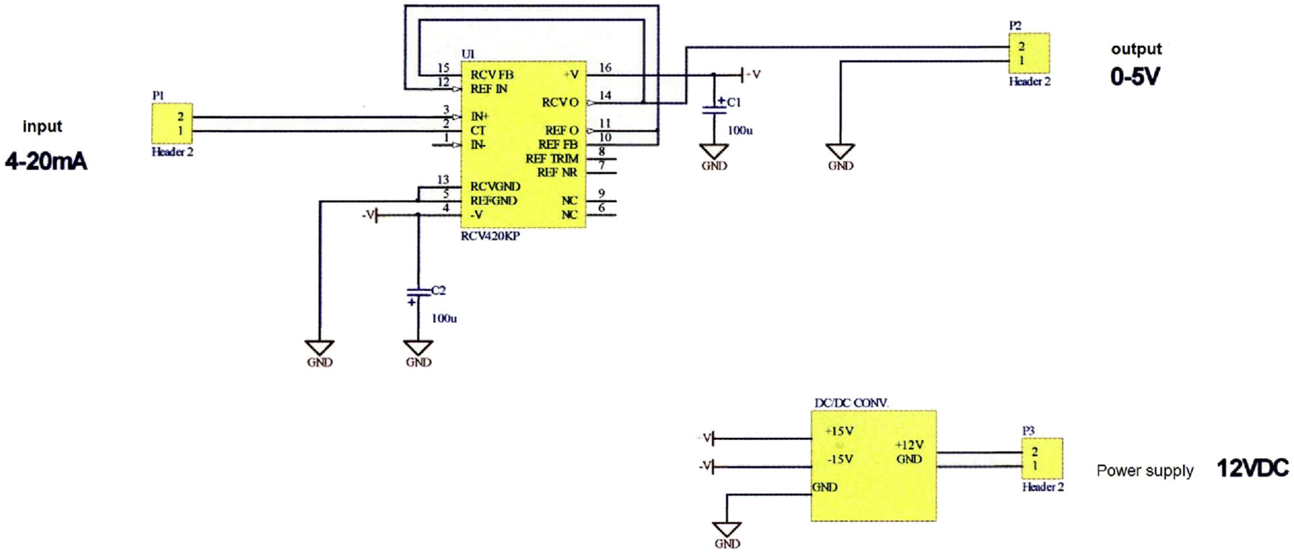

**Fig. 4 – Electric schema of the analog converter.**

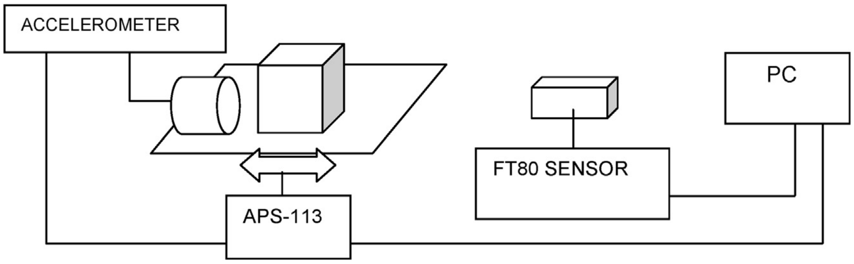

**Fig. 5 – Schematic diagram of sensor calibration.**

from 28 to 120 mm, a frequency range of 0.5–5 Hz, and acceleration from 0.38 to 9.81 $m/s^2$.

In Table 1 the results for selected force parameters are itemized. The maximum deviation between the amplitude p-p of the table, and amplitude p-p indicated by the meter was not greater than 2.3 mm, the total uncertainty is less than 4% for all amplitude ranges measured. Fig. 6 presents a record of the signal from the FT80 sensor for vibration table parameters, these being $a = 9.91$ $m/s^2$, $f = 5$ Hz, $A_{Wp\text{-}p} = 28.11$ mm.

In the laboratory tests, card *A/C NI USB-6210, 16 bit, 250 kS/S and the acquisition* of results from the *LabView* application were used.

### 3.2. *Results of the tests on the testing stand with the impact mass*

The tests performed through dynamic testing and the results obtained have shown that utilizing traditional, known, models based on the classical theory of mechanics and material strength may be disputable in the case of rope testing. When carrying out such work, one should use the results of experiments and probabilistic experimental models.

Typical results of destructive tests are shown in Figs. 7 and 8. The dependence of rope deflection, and force in the rope as function of time, at transverse impact (rope No. 31, Fig. 7), and the dependence of elongation and force in the rope vs. time, at longitudinal impact (rope No. 3 Fig. 8) are presented.

The diagrams presented describe the quality of the measurements obtained with the use of a measurement system, including the laser non-contact sensor used to examine deflection and elongation. The differences in the characteristics of the phenomenon and the capacity of the sensor created to carry out dynamic research, including an oscillatory amplitude, as in Fig. 8, are important here.

### 3.3. *Discussion*

The parameters of the laser equipment for measuring the deformation of mechanical elements, in impact destructive testing were checked in an accredited laboratory for measuring distance from the calibrating vibration table, at a wide range of frequencies (acceleration up to 9.81 $mm/s^2$), and amplitudes of displacement p-p. The maximum deviation between the amplitude p-p of table, and amplitude p-p shown by the instrument was not greater than 2.3 mm, and total measurement uncertainty did not exceed 4% for any of the amplitude ranges.

**Table 1 – Results of calibration measurements on the vibration table APS-113 Electro-Seis.**

| Parameters of vibration table | | | Parameters of device; head-on measurement | | $A_S$-$A_W$ |
|---|---|---|---|---|---|
| Frequency | Acceleration | Amplitude p-p $A_W$ | Frequency | Amplitude p-p $A_S$[a] | |
| Hz | mm/$s^2$ | mm | kHz | Mm | mm |
| 0.5 | 0.38 | 110 | 10 | 110.8 | 0.8 |
| 1 | 1.67 | 120 | 1 | 122.2 | 2.2 |
| 2 | 4.47 | 80 | 10 | 77.7 | −2.3 |
| 4 | 9.81 | 43.93 | 10 | 45 | 1.1 |
| 4 | 9.81 | 43.93 | 1 | 45.6 | 1.7 |
| 5 | 9.81 | 28.11 | 10 | 27.2 | −0.91 |
| 5 | 9.81 | 28.1 | 1 | 28.5 | 0.4 |

[a] Values of maximum divergence.

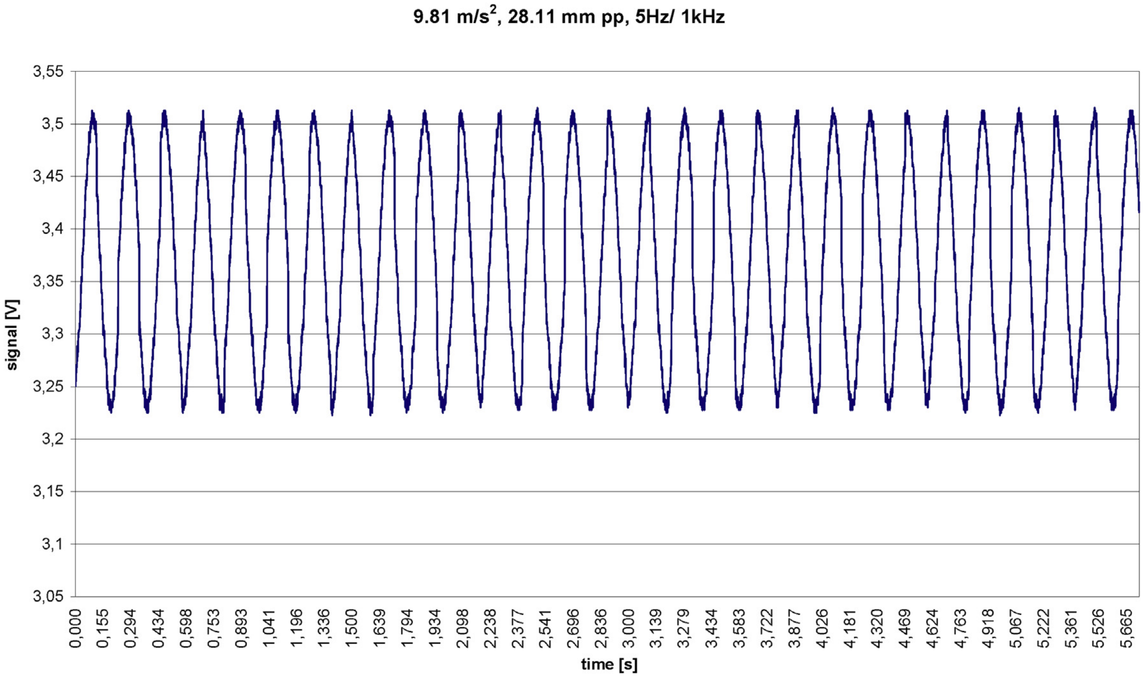

**Fig. 6 – Typical record of the signal from the FT80 sensor; parameters of the vibration table a = 9.91 m/$s^2$, f = 5 Hz, $A_{Wp\text{-}p}$ = 28.11 mm.**

The unit was tested in site conditions, and then implemented in the high-energy testing of ropes on the impact stand in the Central Mining Institute, Katowice. It was shown that the reaction time of 0.4 ms of the sensor enabled the measurement of deflection or elongation of the rope, increasing by 200 mm in 0.2 s, for impact forces in the range of 250–270 kN.

## 4. Conclusions

Calculating the dissipation energy in mechanical protective systems, and thereby determining safety of their usage in mine shafts and other mine workings requires a precise description of deflection and elongation of the rope experiencing either transverse or longitudinal loading with a falling mass. The CMI Laboratory of Laser Technology developed, for this purpose, a measuring instrument based on a fast parallactic rangefinder. It was then mounted, after the testing of laboratory calibration, on a test stand which is an original construction prepared in the Laboratory of Rope Measurement at the same Institute.

The artificial bottom of the shaft, constructed of spread steel ropes, is one of the mechanical protection systems. The efficiency of its operation is linked to an essential parameter which is the elongation or deflection of ropes when loaded with a falling mass. The difficult conditions of creating a test stand with falling mass forced the research team to design a device for the non-contact measurement of distance that would perform measurements in milliseconds. The developed measurement system is equipped with an equatorial laser rangefinder and a fast-acting U/I converter for a measurement card and a recorder of the base station. The recorder also records forces (from strain gauges). The applied system allowed

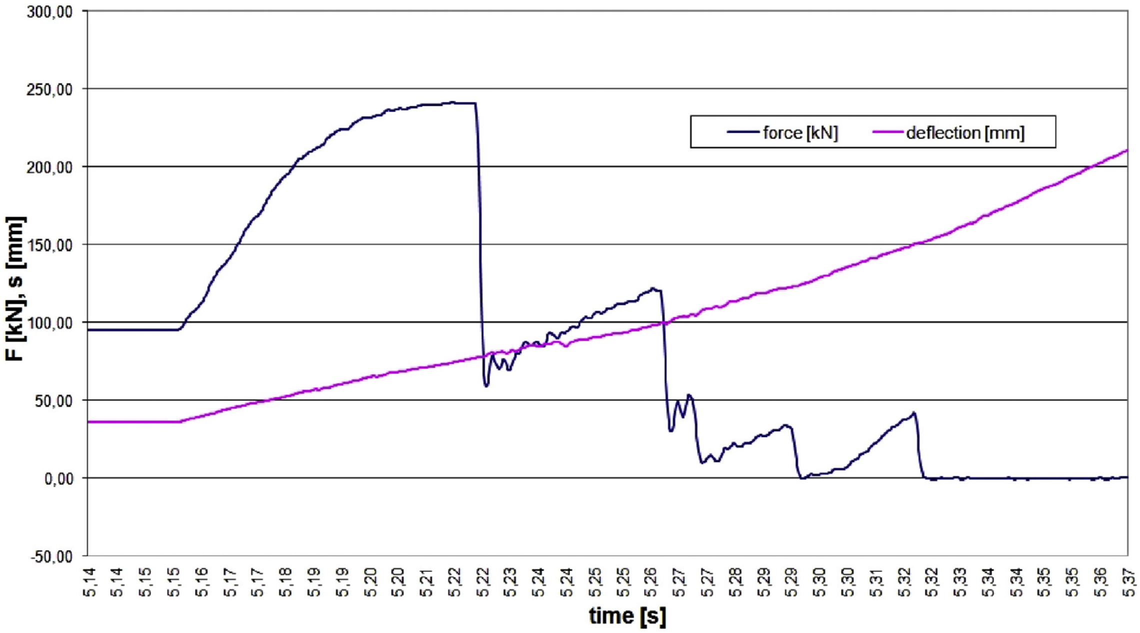

Fig. 7 – Force and deflection of rope vs. time for rope No. 31 (transverse configuration).

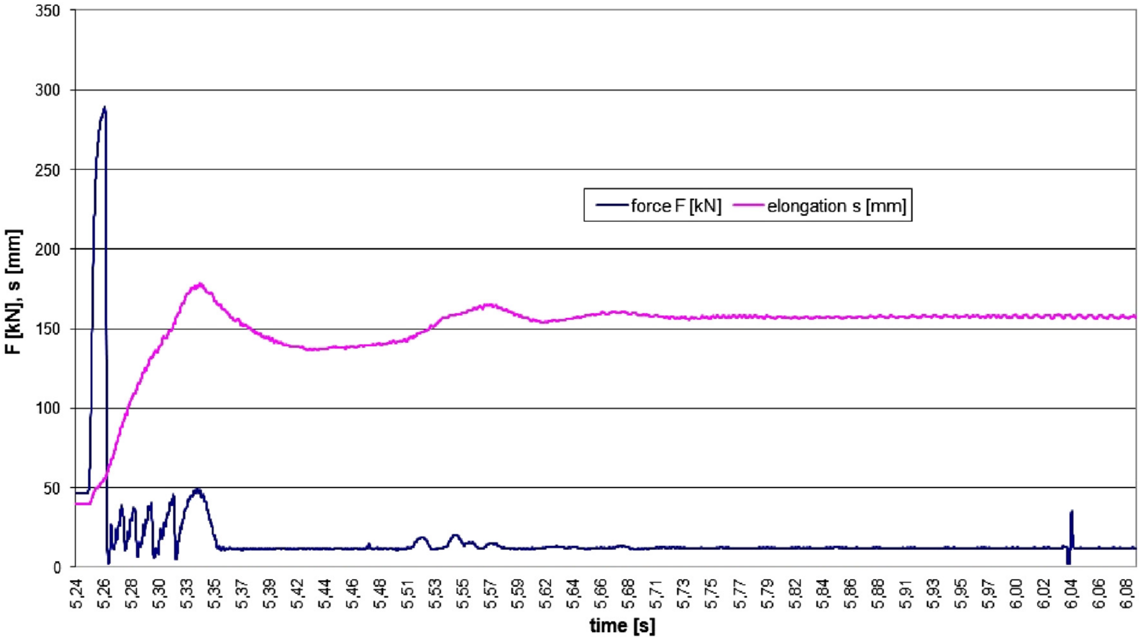

Fig. 8 – Graph of force and elongation vs. time for rope No.3 (longitudinal impact).

the determination of the relationship between longitudinal and crosswise forces, and actual elongation and deflection. So far, such relations could not be registered due to the nature of research and futile attempts to use cable encoders or inductive sensors (mechanical damage and insufficient accuracy).

The calculation of energy dissipation in the roped artificial bottom was also carried out and as a result this made it possible to define the boundaries of the safe use of such systems.

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## REFERENCES

Akai, A., Shiozawa, D., Sakagami, T., Otobe, S., & Inaba, K. (2012, July). Relationship between dissipated energy and fatigue limit for austenitic stainless steel. In *Proc. of the ICEM15 – 15th international conferece on experimental mechanics. New trends and perspectives, Porto/Portugal* (pp. 721–722).

APS-113 Electro-Seis. Retrived (2014) from: www.apsdynamics.com.

Barcikowski, M. (2012). *Wpływ materiałów i struktury laminatów poliestrowo-szklanych na ich odporność na udar balistyczny (Effect of material and structure of polyester-glass laminates on ballistic impact)*. *praca doktorska* (Ph.D. thesis). Zachodnopomorski Uniwersytet Technologiczny w Szczecinie. Retrived (2014) from www.academia.eu.

Białożyt, T., Bochenek, W., Passia, H., Smoła, T., Szade, A., & Szot, M. (2008). New developments of laser-based measuring equipment for control of the condition of vertical and horizontal mine workings and structures in mining-affected areas. In *New challenges and vision for mining – New technologies in mining* (pp. 117–123). Kraków: Wyd. EJB (Proc. of the World Mining Congress).

Distance Sensors SensoPart. (2014). *Czujnik FT 80 RLA*. Retrived (2014) from: www.sensopart.de.

Hankus, J. (2000). *Budowa i własności mechaniczne lin stalowych* (Wyd. II). Katowice: Główny Instytut Górnictwa.

HBM Operation Manual. (2002). Operation Manual, PC measurement electronics Spider8, Hottinger Baldwin Messtechnik GmbH, Retrived (2010) from www.hbm.com.

ISO 16 063-41. (2011). *Methods for the calibration of vibration and shock transducers. Part 41 calibration of laser vibrometers*.

La Rosa, G., & Risitano, A. (2000). Thermographic methodology for rapid determination of the fatigue limit of material and mechanical components. *International Journal of Fatigue, 22*, 65–73.

Lipski, A., & Mroziński, S. (2008). *Termowizyjna analiza zmiany temperatury w trakcie monotonicznego rozciągania próbki stalowej bez wyraźnej granicy plastyczności (Thermal analysis of the temperature changes during monotonic tensioning of steel sample without a defined yield point)*. In *Materiały XXII Sympozjum Zmęczenie i mechanika pękania* (pp. 193–200). Bydgoszcz.

Passia, H., Kompała, J., & Szade, A. (2012, July). Diagnostics of technical condition of various building structures based on monitoring using purpose – designed laser and acoustic equipment. In *Proc. of the ICEM15 – 15th international conference on experimental mechanics. New trends and perspectives, Porto/Portugal* (pp. 977–978).

Pałkowski, Sz. (1994). Konstrukcje cięgnowe *(Constructions based on flexible connectors)*. Warszawa: Wydawnictwa Naukowo–Techniczne.

Pieczyska, E. A. (1999). Thermoelastic effect in austenitic steel referred to its hardening. *Journal of Theoretical and Applied Mechanics, 37*(2), 349–368.

Pytlik, A. (2002). Badania odporności udarowej kotwi górniczych (Investigation of impact resistance of mining rock bolts. *Prace Naukowe GIG. Górnictwo i Środowisko, 2*, 25–41.

Siemieniec, A. (2002). *Eksperyment w wytrzymałości materiałów*. (Mechanical strenght of materials – experiment). In S. Wolny (Ed.), Wytrzymałość materiałćw. (Part IV). Kraków: Akademia Górniczo-Hutnicza.

Zukas, J. A. (1990). *Hight velocity impact dynamics*. U.K.: J. Wiley& Sons Inc.