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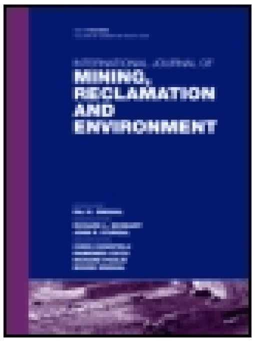

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Testing belt conveyor resistance to motion in underground mine conditions

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ABSTRACT

This paper presents a method of measuring the resistances to motion of a single three-roller idler set with the use of a specially designed measuring stand. The design and calibration of the stand are described. The stand allows to conduct measurements in real operating conditions and with variable stream of bulk material. The frame with the data acquisition equipment is mobile and thus allows the measuring system to be installed in any point along the route of any belt conveyor. A base (reference) belt conveyor representative for the group of belt conveyors used in copper ore mines was selected for the tests. The results of research into the resistance to motion of a single carrying idler set are presented. The measuring system enabled determination of the loading of the tested idler set in the whole range of belt conveyor capacity. Owing to this fact, the dependence between the motion resistance of a single carrying idler set and the mass capacity was determined. The degree of belt conveyor loading was found to have a significant impact on the values of motion resistances generated by a single three-idler set.

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Idler; belt conveyor; resistance to motion; mining; main resistances to motion; field measurements

1. Introduction

In recent years in Poland, a conservative approach to the design of belt idler set support systems could be observed. This conservatism is partly due to uncritical acceptance of standards specifying safe ranges. The latter often have an excessive margin of safety, whereby they are not always optimal. The pilot industrial installations of long-distance belt conveyors constructed both worldwide [1] and in Polish mining industry [2,3] contradict some of the accepted and commonly used design solutions. This contradiction is also highlighted by the results and economic effects of research and development studies dealing with the optimisation of belt conveyor designs carried out for PGiE KWB Belchatow S.A., which led to implementation of the designs in 2010 [4]. The main aim of the research was to indicate possibilities for the reduction of belt conveyor drives energy consumption and to present the technical means for achieving them [5–10].

The belt conveyors that are operated in the underground mines of KGHM Polska Miedz S.A. were mostly designed in the 1990s. The planned mining of new copper ore deposits situated deep and far off the existing main (transportation) shafts, creates a need to seek new efficient and economically viable belt conveyor solutions.

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It should be noted that the final solution of continuous transport system will be equipped with modern automation and monitoring systems with decision support algorithms. These issues have been widely presented in the literature, among others in [4,11–13]. However, one of the solutions which fit into the Company's innovation strategy is the use of belt conveyors with significantly reduced resistances to motion. Since the experience acquired from the research on optimal solutions for opencast brown coal mines cannot be directly applied to much smaller underground belt conveyors – mainly due to different types of belts employed, different (more compact) belt conveyor structures and more difficult installing and operating conditions – a project to develop a new energy-saving belt conveyor was launched in KGHM PM S.A. The modernisation efforts were divided into three main areas and consisted in the use of energy-saving belts, idlers with reduced rotational resistance and drive units with enhanced efficiency. A schedule of research aimed at reaching the established goals was prepared. The results of the investigations were published in [14,15].

In case of horizontal and *quasi*-horizontal belt conveyors, main resistances constitute the biggest part of conveyor resistance to motion. Main resistances consists of idler rotational resistance W_k, indentation rolling resistance W_e, belt bending resistance (flexure resistance of a belt) W_b, flexure resistance of bulk material W_f, sliding resistance of a belt on idlers W_r. Idler rotational resistance and indentation rolling resistance have a significant impact on energy consumption of belt conveyors [16]. The conducted analyses showed that the sum of these two components can account for up to 70% of total belt conveyor resistance to motion [5,17]. Greatest energy consumption reductions may result from adequate belt and idler selection, from optimal spacing of carrying idler sets, and in some cases also from unconventional solutions used in the design of routes, take-up arrangements and transfer chutes [10,18].The results of research and development works done at the Wroclaw University of Technology, Machinery Systems Division, have shown that one of the conditions for successful reduction of the energy consumption of belt conveyor drives is to use high-quality idlers characterised by low rotational resistance under a wide range of working loads [7,8] and energy-saving conveyor belt characterised by low indentation rolling resistance [19, 20].

This paper presents the results of experimental research into the resistance to motion of a single three-roller idler set positioned on the route of a selected base (reference) conveyor. The aim of the study was to determine a benchmark that would allow to measure energy savings generated by the use of a variety of components introduced in a prototype energy-efficient belt conveyor.

2. Description of measuring method

Figure 1 illustrates the concept behind the measurement of a single carrying idler set's resistances to motion. The term 'carrying idler set' is here used in accordance with its common definition as a set of rolls supporting the belt and the material on the belt and will be later in this article referred to as 'the idler set'. The measuring idler set thus defined comprises a set of three carrying idlers and is installed on a specially constructed measuring unit of belt conveyor route equipped with six strain-based force gauges. The tested idler set is suspended from a special crossbar and is hinge-supported on two gauges measuring vertical forces F_1 and F_2, and registering the tensile force.

During measurements, the sum of the two forces represents the resultant vertical load acting on the idler set. The load is composed of the idler set belt weight and the instantaneous weight of bulk material. This means that instantaneous conveyor capacity is also measured. Before each measurement, the crossbar with the hinge-supported set is lowered (using rigging screws) below the belt to register the gravity force of those elements of the set, which must be later deducted from the total reading of the force gauges. The measuring set is held with articulated joints on both sides and supported in the horizontal plane by two pairs of narrow-range force gauges. Differences between the readings given by the four force gauges are the basis for determining the instantaneous horizontal force at the belt/idlers contact area while the belt is running. The total resistance to motion per idler set is measured by two pairs of force gauges (F_3 and F_4, F_5 and F_6) located on both sides of the set and fixed to the

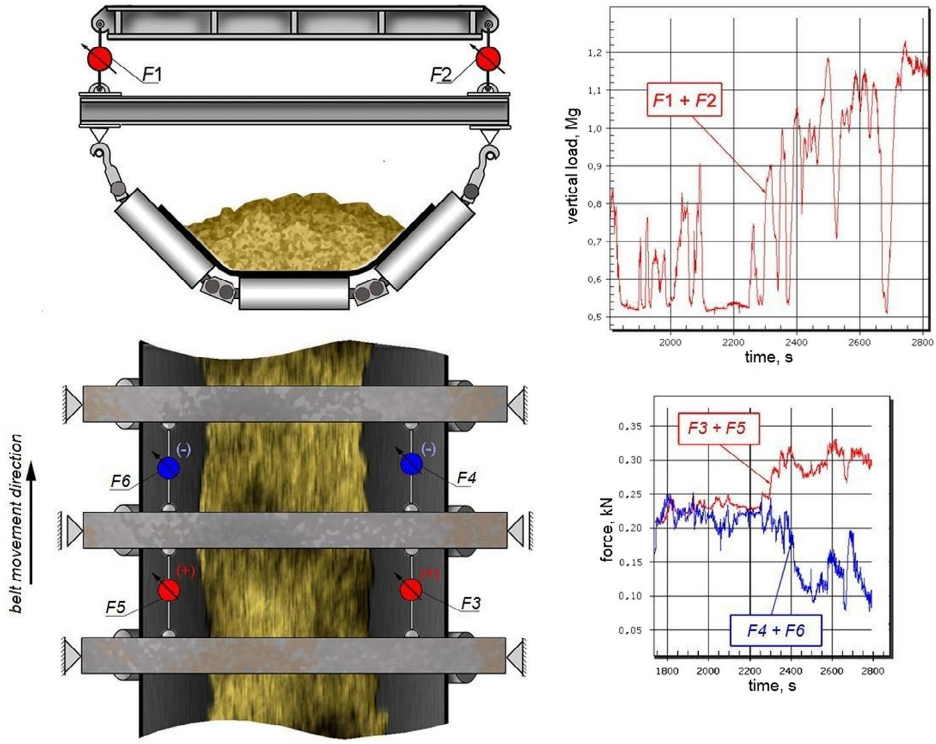


Figure 1. Measuring idler set with force gauges.

horizontal elements. It should be noted that during belt movement horizontal forces registered by the gauges change as follows:

- forces F_3 and F_5 increase by, respectively, ΔF_3 and ΔF_5, due to the direction of the horizontal force of mutual interaction between the belt and the rollers:

$$F_3 = F_{30} + \Delta F_3 \tag{1}$$

and

$$F_5 = F_{50} + \Delta F_5 \tag{2}$$

- forces F_4 and F_6 decrease relative to their initial values, due to the horizontal force of mutual interaction between the belt and the rollers:

$$F_4 = F_{40} - \Delta F_4 \tag{3}$$

and

$$F_6 = F_{60} - \Delta F_6 \tag{4}$$

In order to determine the total resistance to motion per measuring set, one should add all the force increments registered by the horizontal gauges, i.e.

$$W_g = \Delta F_3 + \Delta F_4 + \Delta F_5 + \Delta F_6 \tag{5}$$

Thus, using relation (5), one can determine the instantaneous motion resistance values on the basis of the traces recorded by the four force gauges.

If belt tensioning force does not occur, which is the case when the neighbouring idler sets are aligned with the measuring set, the resultant horizontal force measured by the four gauges may be assumed to represent the total motion resistance of a single idler set. During the experiment, two preceding idler sets and two succeeding idler sets of the measuring stand were levelled relative to the measuring stand. Therefore, no effect of weight component is observed on the measured resistance to motion.

3. Testing and calibration of mobile measuring stand

In order to test the resistance to motion, which occurs on a single three-roll idler set, a mobile measuring stand was designed and built. Figure 2 shows a 3D model of the mobile measuring stand while the assembly drawing is shown in Figure 3. Owing to its design, the stand can be easily and quickly assembled at any point along the conveyor route, without disturbing the structure of the conveyor's

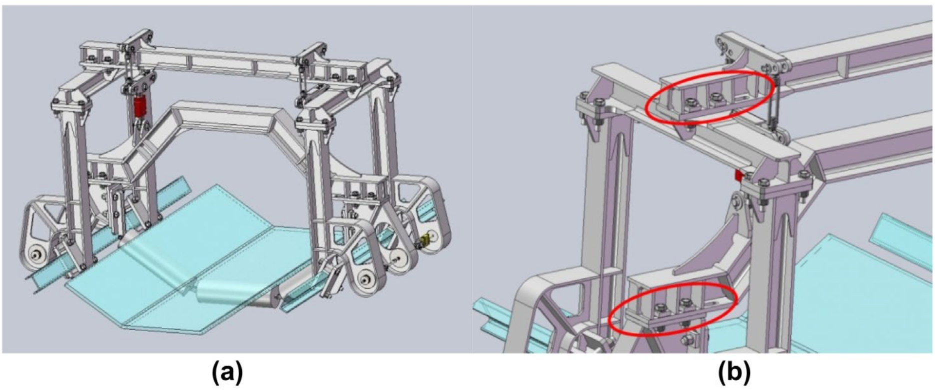


Figure 2. 3D model of mobile measuring unit: (a) general overview, (b) view of the universal mounting flange.

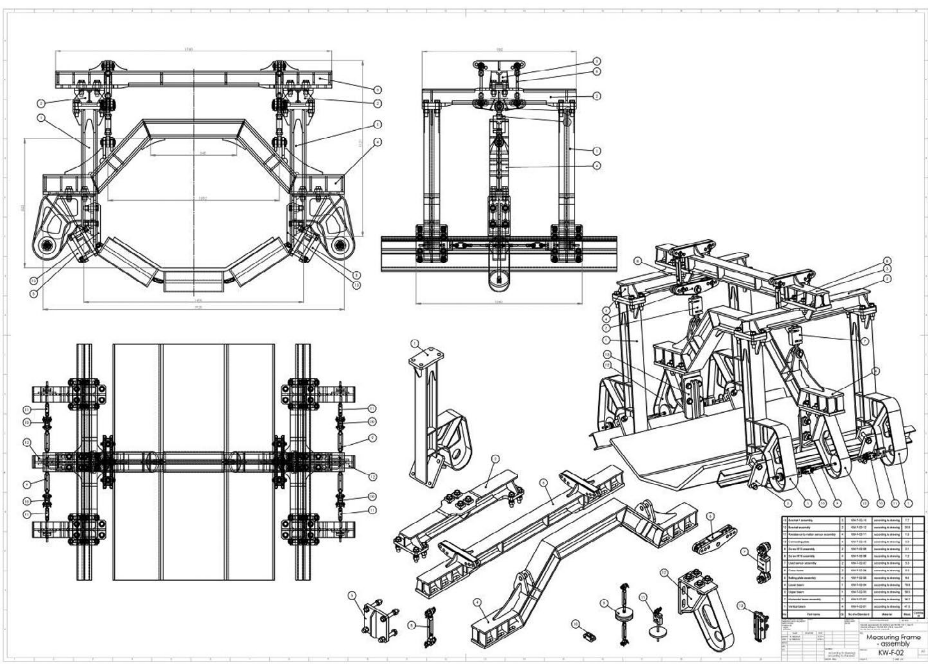


Figure 3. Assembly drawing of the measuring unit structure.

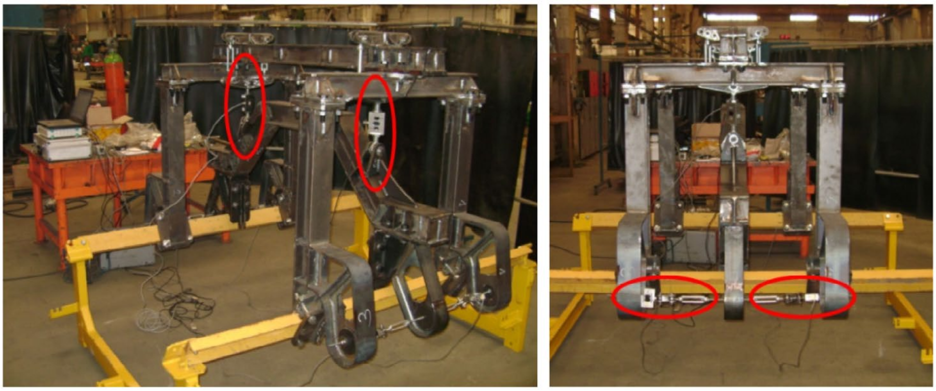


Figure 4. Measuring unit view with force gauges.

load-bearing elements. Moreover, the design fits both 1000 and 1200 mm conveyors. The whole measuring set is equipped with two symmetrically located load gauges measuring the vertical load acting on the idler set and with four gauges in the horizontal plane, measuring the resultant horizontal force acting along the longitudinal axis of the belt (the resultant motion resistance of the idler set). The measurement frame design allows for quick adjustment and can be adapted to specific operating conditions, such as belt width and idler set load. As a result, resistances to motion can be measured on any belt conveyor under its typical operating conditions.

When designing the measurement frame, several technical requirements were taken into account. The required features included the following:

- Suitable stiffness of the frame, adaptable to the 1000- and 1200 mm-wide conveyor route structure,
- the possibility to disassemble the device into conveniently small parts to be easily transported and assembled at any point along the belt conveyor route,
- the possibility to level the measuring set and suitably position it relative to the neighbouring idler sets.

The measurement frame of the mobile measuring stand was manufactured and then assembled on the production floor of KGHM ZANAM Sp. z o.o. Figure 4 shows a view of the assembled frame with gauges. The measuring signal was registered and transmitted from the force gauges using a SPIDER 8.0 amplifier connected to a computer equipped with Hottinger Catman Easy software, which enables recording, processing and analysing measurement signal changes. Hottinger S9 gauges with a measuring range of 20 kN were used to register vertical forces, while S2 gauges with a measuring range of 500 N were used to register resistance to motion.

During the design stage of the measurement frame, the kinematic diagram of the system was analysed. The examination involved active forces generated by the weight of a three-roller idler set and the reactions they caused. The system's kinematic diagram is shown in Figure 5. The sum of the forces originating from the suspended set, the belt weight and the weight of the transported bulk material is denoted as F_V, while the forces connected with the motion resistance of the single three-idler set are represented by F_H. Assuming that the forces acting in the vertical plane and in the horizontal plane are in equilibrium and that particular elements are connected with articulated joints, the following equation of equilibrium for the vertical forces may be established:

$$F_V = F_1 + F_2 \tag{6}$$

where: F_V – the resultant vertical loading force, kN; F_1, F_2– the registered vertical forces, kN.

In the horizontal plane, there is assumed equilibrium of the forces originating from the motion resistance of a single idler set and from the reaction forces measured by gauges F_3 to F_6. Before

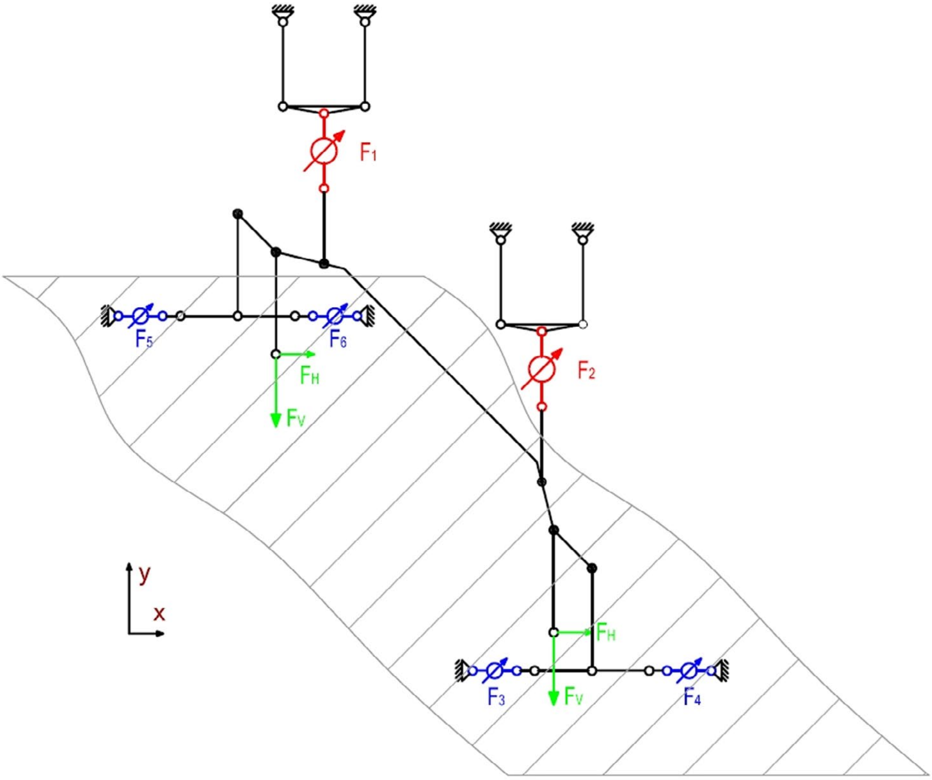


Figure 5. Kinematical diagram of measuring system.

measurements, the gauges were preloaded to half of the measuring range. For the measuring plane, the following equation of the equilibrium of forces is obtained:

$$F_H = F_3 - F_4 + F_5 - F_6 \tag{7}$$

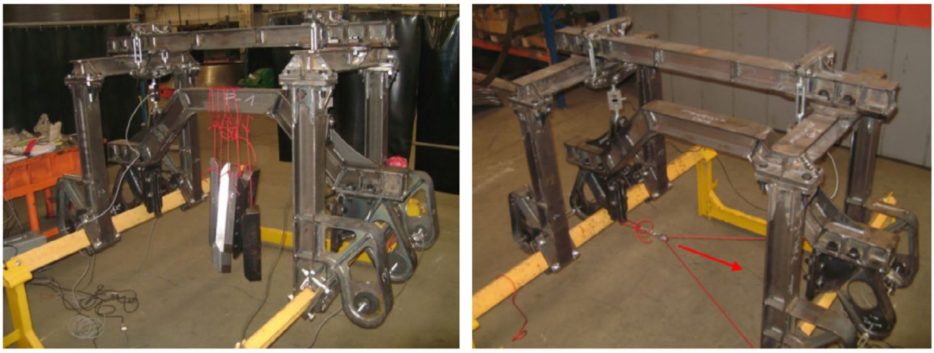
where: F_h – the force of the motion resistance of a single idler set, N; F_3, F_4, F_5, F_6 – the horizontal forces being registered, N.

Three possible cases of different loading were analysed, with attention paid to the effects of the phenomena that might occur along the belt conveyor route in real operating conditions (e.g. side movement due to mistracking). A view of the measuring system during calibration is shown in Figure 6. Accuracy of the readings from the installed force gauges was analysed in the following cases:

- the application of vertical load, shown in Figure 6(a),
- the lateral displacement of the crossbar, shown in Figure 6(b),
- the action of applied vertical force and of horizontal force, shown in Figure 7.

During the first two stages of calibration, reading accuracy of the mounted vertical and horizontal force gauges was tested in respect of both applied vertical force and lateral displacement of the crossbar, separately. The impact of applied vertical force on the reading accuracy of force gauges was analysed with the use of known applied vertical force; this stage of calibration is shown in Figure 6(a). The impact of the lateral displacement of the crossbar on the reading accuracy of force gauges was analysed with the use of applied lateral displacement of the crossbar; this stage of calibration is shown in Figure 6(b).

The third stage of calibration was performed with regard to the level of forces acting on the elements of the belt conveyor during normal operation. During this stage of calibration, the accuracy of both



(a) (b)

Figure 6. View of calibration of measuring system: (a) application of the vertical load, (b) lateral displacement of the crossbar.

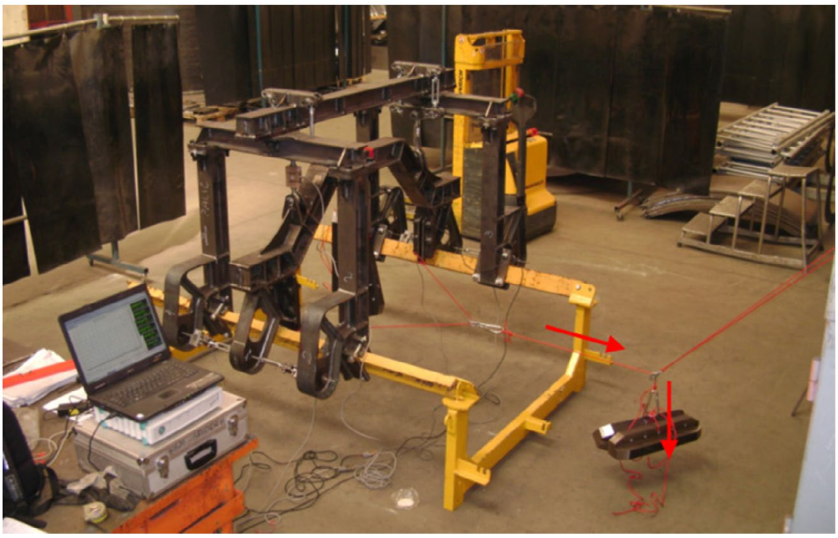


Figure 7. View of calibration of measuring system with use of applied vertical and applied horizontal force.

Table 1. Effect of the action of applied vertical force and applied horizontal force on vertical force gauges reading accuracy.

Applied force	Force gauges		Calculated force	Calibration error		Absolute error	Total absolute error	Total Relative Error
F_{VApp}	F_1	F_2	F_V	–		$\Delta F_1, \Delta F_2$	$\Delta F_1 + \Delta F_2$	$\delta F_1 + \delta F_2$
[N]	[N]	[N]	[N]	[N]	[%]	[N]	[N]	[%]
269.7	819	911	274	4.30	0.02	10.00	20.00	0.023
539.5	962	1052	558	18.50	0.03			0.020
696.5	1043	1129	716	19.50	0.03			0.018

vertical and horizontal force gauges was tested simultaneously. Results are presented in Tables 1 and 2. For this purpose, a possible force system acting on the measuring idler set was analysed. According to the measuring unit's design, all of the force gauges are connected with articulated joints. This type of connection allows to perform calibration making allowance for friction forces occurring on pivots.

Table 2. Effect of the action of applied vertical force and applied horizontal force on horizontal force gauges reading accuracy.

Applied force	Force gauges				Calculated force	Calibration error		Absolute error	Total absolute error	Total relative error
F_{HApp}	F_3	F_4	F_5	F_6	F_H	–		$\Delta F_3, \Delta F_4, \Delta F_5, \Delta F_6$	$\Delta F_3, \Delta F_4, \Delta F_5, \Delta F_6$	$\delta F_3+\delta F_4+\delta F_5+\delta F_6$
[N]	[N]	[N]	[N]	[N]	[N]	[N]	[%]	[N]	[N]	[%]
269.7	347.1	218.4	325.4	177.5	276.6	6.90	1.23	0.25	1.00	0.004
539.5	425.2	168.9	395.9	132.2	520.0	−19.50	3.19			0.005
539.5	426.8	170.2	397.5	132.5	521.6	−17.90	3.17			0.005

The calibration process was, therefore, conducted in conditions simulating operating conditions of the belt conveyor.

Calculation of resistance to motion and vertical load of the single carrying idler set on the basis of force gauges readings is made with some accuracy, which is connected with the uncertainty of the measurement. For measurement of vertical force (Figure 1), S9 type force gauge was used, manufactured by Hottinger Baldwin Messtechnik GmbH with measuring range up to 20 kN and accuracy class of 0.05. Measurements of horizontal forces were made with the use of S2 type gauge from the same manufacturer. Measurement range of S2 type gauge is up to 500 N, the accuracy class is the same as in the case of S9 gauges. Before the measuring process, horizontal gauges were preloaded up to 50% of measuring range (Figure 1). In addition, the measuring range of the gauges is bigger than the expected value of the measured horizontal forces. An important requirement for the gauge is to withstand the peak loads that can appear during normal operation of belt conveyor and have a negative impact on the force gauges, or even destroy them. Therefore, horizontal force gauges with the range up to 500 N are necessarily used, despite the relatively small calculated resistance to motion (20–45 N). During downtime of the belt conveyor, all horizontal force gauges are preloaded up to approx. 250 N, although during belt conveyor's normal operation readings from horizontal force gauges change within the range of 150–350 N. Resistance to motion is calculated on the basis of readings from horizontal force gauges according to Equation 5. Absolute error (Δ) of a single S9 type force gauge is 10 N. For two S9 gauges located in the measuring system, the total absolute error is the sum of absolute errors of each force gauge ($\Delta F_1+\Delta F_2$) and reaches up to 20 N. Absolute error of single S2 type force gauge is 0.25 N; thus for four S2 gauges installed in the measuring system, the total absolute error is sum of absolute errors of four gauges ($\Delta F_3+\Delta F_4+\Delta F_5+\Delta F_6$) and reaches up to 1 N. Absolute and relative errors calculated for vertical and horizontal force gauges are shown in Tables 1 and 2.

4. Test on experimental belt conveyor

The operational measurements were carried out on the L-1031 conveyor with a 1000 mm-wide belt, working in the EAST region of the KGHM Lubin mine, whose specifications are as follows:

- Belt conveyor type Legmet H1000
- Length, L 530 m
- Conveyor belt width, B 1000 mm
- Speed of conveyor belt, v_t 2.0 m/s
- Idlers spacing, l_k 0.83 m
- Drive system specification:
- Number of electric motors 2
- Type of electric motors 2SIE 315M6D
- Power of electric motors 2 × 160 kW 50 Hz, 500 V
- Clutch type VOITH TVVSN
- Gear type PLC40 – R10-G12-25
- Gear ratio 1:25
- Brake type Disk brake OMEGA 200
- Average slope 1°39′
- Expected load 400 Mg/h

Figure 8 shows a view of the belt conveyor and the mobile measuring unit on which the motion resistance of a single carrying idler set was measured.

During the measurements, records were taken of the trace of the resultant vertical force, which is the sum of the readings from the two side force gauges F_1 and F_2 (Figure 9), and the trace of the resultant horizontal force, as the total signal from the four force gauges: F_3, F_4 (Figure 10) and F_5, F_6 (denotations consistent with Figure 1). The vertical resultant force is the measure of the instantaneous capacity of the belt conveyor, while the horizontal resultant force is the measured motion resistance per idler set.

5. Measurement results

Measurements performed in mine conditions allowed to record the real forces that exert load on the tested measuring set and to determine the motion resistances of the set. The variation in the vertical forces over time is shown in Figure 11. The resultant vertical force is a measure of the instantaneous capacity of the conveyor, while the resultant horizontal force is the measured resistance to motion per idler set (Figure 12).

Figure 8. View of the conveyor and the assembled measuring unit.

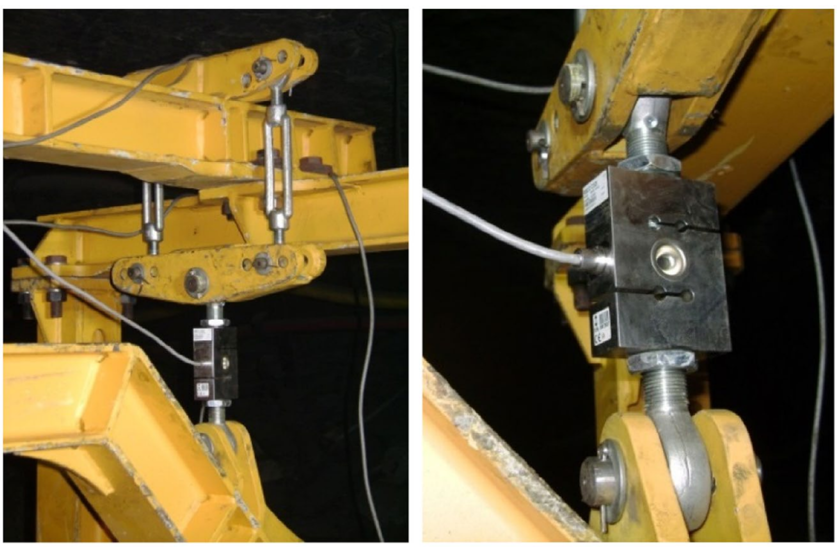


Figure 9. Gauges registering resultant vertical load $F_{v.}$

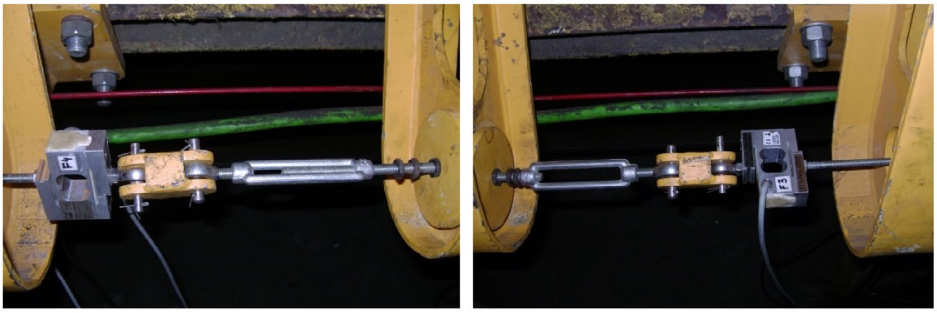


Figure 10. Gauges registering horizontal forces F_4 and $F_{3.}$

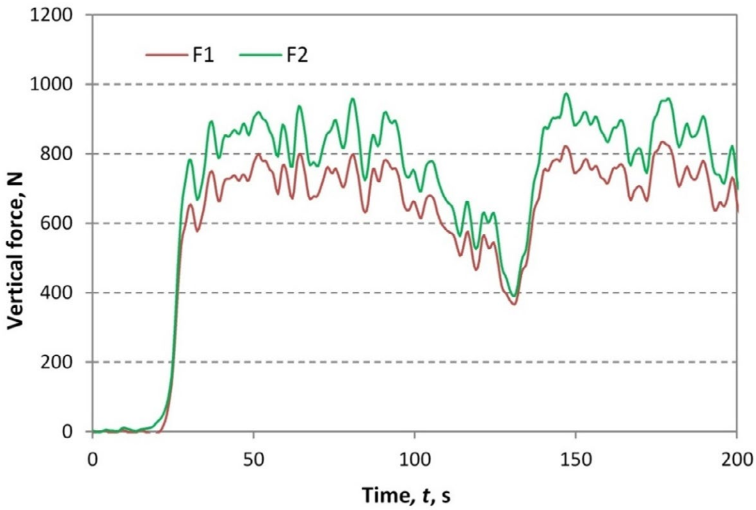


Figure 11. Exemplary traces of instantaneous vertical forces.

The indications of the force gauges were continuously recorded during one working shift. Figure 13 shows the idler set's motion resistance, according to the research results, as a function of recorded vertical load F_V. The measurements are contained within the vertical force range of up to about 2 kN – the value corresponding to the rated loading of the belt with bulk material. This allowed to obtain a number of measuring points, showing a distinct functional dependence.

In order to determine the energy consumption of the base (reference) belt conveyor, against which energy-saving effects will be compared, it is necessary to convert resultant vertical force F_V into mass capacity Q_m. Recorded resultant vertical force F_V acting on the idler set, induced by the deadweight of the belt and the instantaneous bulk material weight, amounts to:

$$F_V = l_k \cdot g \cdot (B \cdot m_t + m_u) \quad \text{in N}, \tag{8}$$

where: l_k – the spacing of the carrying idler sets, m; B – the width of the belt, 1.00 m; m_t – the specific weight of the belt, 21,74 kg/m^2; g – gravitational acceleration, 9.81 m/s^2; m_u – the linear weight of the bulk material, kg/m.

The instantaneous conveyor belt capacity amounts to:

$$Q_m = m_u \cdot v_t \quad \text{in kg/s}, \tag{9}$$

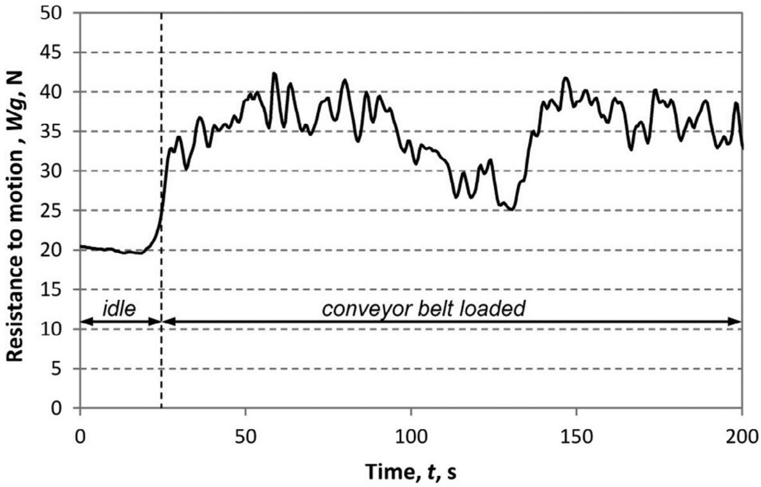


Figure 12. Exemplary variation in resistance to motion of idler set.

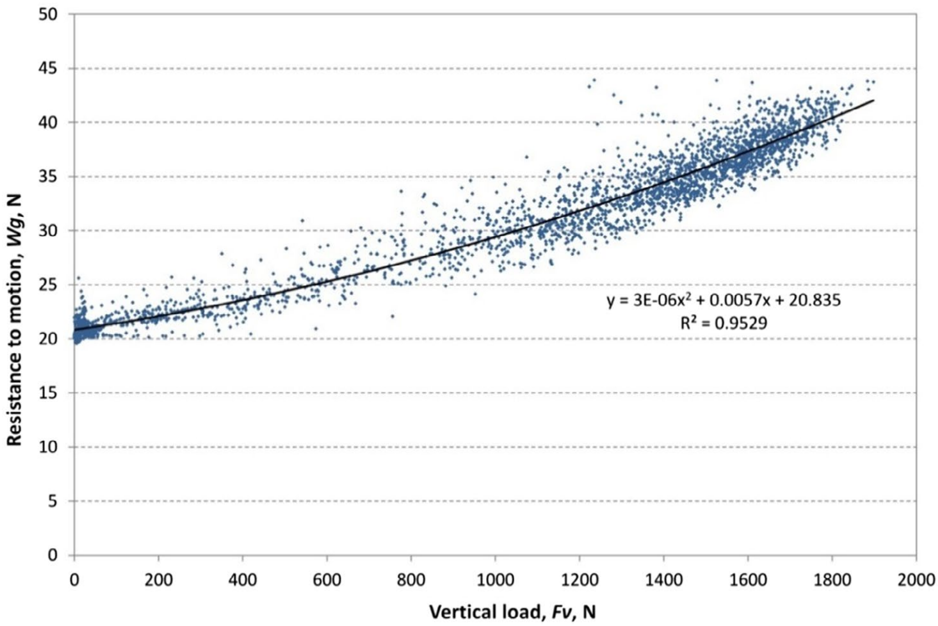


Figure 13. Set of measuring points illustrating dependence between motion resistance of single idler set and vertical load $F_{V.}$

or:

$$Q_m = 3,6 \cdot m_u \cdot v_t \quad \text{in Mg/h}, \tag{10}$$

where: v_t – the belt speed, m/s.

Hence the mass capacity expressed in Mg/h, determined on the basis of the resultant vertical force, is calculated from the relation:

$$Q_m = 3,6 \cdot \left(\frac{F_V}{l_k \cdot g} - B \cdot m_t \right) \cdot v_t \tag{11}$$

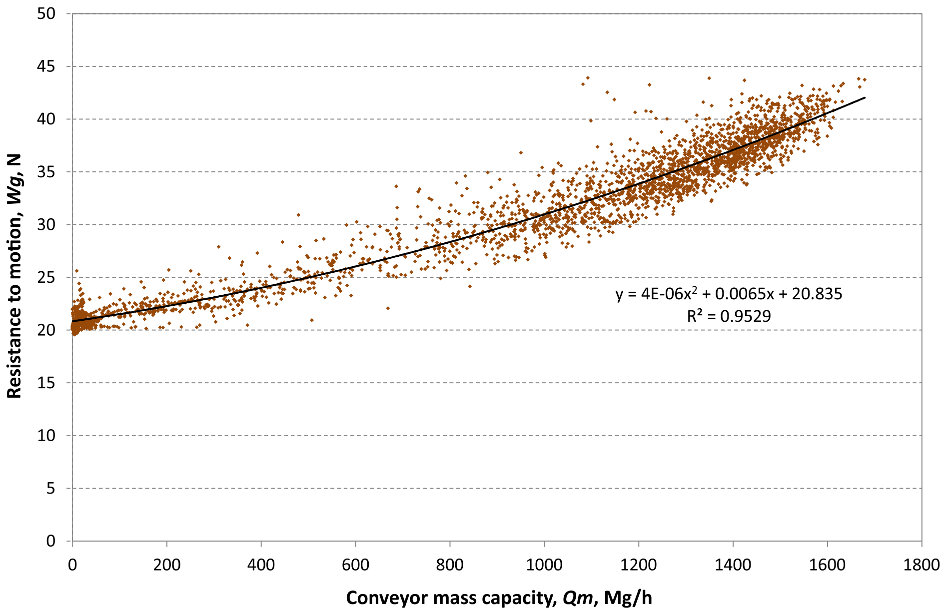


Figure 14. Single idler set motion resistance vs. mass capacity.

The nature of the variations in idler loading was described as a linear regression function. For this purpose, a polynomial trend line of the 2nd degree was determined for the recorded measurement series. Fit coefficient R^2 obtained for the trend line was very high and amounted to 0.95.

The visible changes in the resistance to motion of the tested idler set are due to changes in the amount of the stream of material on the conveyor. Therefore, changes in instantaneous motion resistance values need to be always analysed in correlation with the random variation in the bulk material stream. The determined dependence between single idler set motion resistance W_g and mass capacity Q_m is shown in Figure 14.

6. Conclusion

The accuracy of the available computing methods is vital in analyses aimed at determining the effect of belt conveyor design parameters on its resistances to motion. In order to verify the methods, measuring belt conveyor resistances to motion appears a necessity. The proposed measuring method, based on registering forces in a hinged system supporting the measuring crossbar, was found to be useful in the operational testing of a belt conveyor in underground mine conditions. Calibration confirmed high accuracy of the proposed measuring method and the recording-measuring apparatus proved to be fully useful. The experiment allowed to determine resistances to motion of a single idler set of the belt conveyor in the whole range of the randomly variable stream of bulk material. A distinct effect of the degree of belt conveyor filling on the values of was observed. The amount of bulk material on the conveyor belt was observed to have significant influence on the registered values of motion resistance.

Disclosure statement

No potential conflict of interest was reported by the authors.

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