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SIMULATION STUDIES AS THE PART OF AN INTEGRATED DESIGN PROCESS DEALING WITH BELT CONVEYOR OPERATION

BADANIA SYMULACYJNE JAKO ELEMENT ZINTEGROWANEGO PROCESU PROJEKTOWANIA W ASPEKCIE EKSPLOATACJI PRZENOŚNIKÓW TAŚMOWYCH*

This article presents simulation studies of transient working states of a conveyor as an indispensable, important part of the integrated process of its design. Simplified block diagrams and equations describe the structure of a dynamic model of a belt conveyor and a gravity take-up system. Results of simulation studies on the belt conveyor model have been compared to results of industrial tests carried out at the site of the conveyor operation using a mobile measurement system. The results of verifying the dynamic model have confirmed its utility for analysing dynamic phenomena occurring when the conveyor is operated, and demonstrated the complete suitability of simulation studies in the integrated process of designing belt conveyors.

***Keywords**: conveyors, belt take-up systems, simulation studies, dynamic analysis, computer-aided design.*

W niniejszym artykule przedstawiono badania symulacyjne nieustalonych stanów pracy przenośnika, jako nieodłączną i istotną część zintegrowanego procesu jego projektowania. Za pomocą uproszczonych schematów blokowych i równań, opisano budowę dynamicznego modelu przenośnika taśmowego oraz grawitacyjnego urządzenia napinającego taśmę. Wyniki testów symulacyjnych modelu przenośnika taśmowego porównano z wynikami badań przemysłowych, przeprowadzonych w miejscu eksploatacji przenośnika z wykorzystaniem mobilnego systemu pomiarowego. Wyniki weryfikacji modelu dynamicznego potwierdziły jego użyteczność w analizie zjawisk dynamicznych występujących podczas pracy przenośnika oraz wykazały pełną przydatność badań symulacyjnych w zintegrowanym procesie projektowania przenośników taśmowych.

***Słowa kluczowe**: przenośniki taśmowe, urządzenia napinające taśmę, badania symulacyjne, analiza dynamiczna, komputerowe wspomaganie projektowania.*

1. Introduction

Due to their transport capacity and reliable operation, belt conveyors play a dominant role in systems for hauling useful minerals, both in open pit and underground mines. Belt conveyors transporting overburden can achieve capacities of 50,000 tons/h, the length of single installations can reach 20 km, and the power of their drives 12 MW. Belt conveyors with the greatest capacities, belt speeds and installed powers are used to transport overburden in open pit lignite mines, while designers face many interesting engineering challenges when designing overland conveyors more than ten kilometres long, designed for operating in difficult terrain and climate, as well as variable length belt conveyors used for drilling tunnels or working in underground hard coal mines [12].

Due to their operating environment and transport tasks, modern belt conveyors require the use of belts manufactured using state-of-the-art technologies, their drives are equipped with increasingly advanced and complex control systems, while belt support systems are optimised according to the criterion of cutting costs and increasing their durability. Many belt conveyors currently built are fitted with equipment tensioning the belt as a function of load on the driving system of the conveyor. New designs of conveyors must be drawn up using specialised software with constantly extended computational algorithms, making use of the latest results of industrial and operational research as well as laboratory experiments [12, 16]. State-of-the-art computer applications used globally to aid design activities exemplify the integrated design of belt conveyors with multi-option calculations, verifications and the selection of belt conveyor subassemblies, analyses of dynamic states and simulation studies conducted to select the best option according to assumed criteria [10, 12].

2. Integrated design of a belt conveyor

Belt conveyors are modular in structure and their designer's main job is to correctly select and combine ready subassemblies into a unique machine executing the planned transport task. The design of conveyors comprises a set of integrated processes executed by a design team, which encompasses analysing the transport task, the conditions and limitations of its execution, selecting operational parameters, making basic calculations, completing conveyor subassemblies taking into account economic conditions, as well as laboratory testing and simulation studies to adjust the operating parameters and set-points of control systems (Fig. 1). Machine examinations in industrial conditions to verify and calibrate computational models as well as accounting for the results of operational and diagnostic testing of selected belt conveyor components in the design process represents an important part of the integrated design of belt conveyors [5–7, 14–15, 18].

For belt conveyors, the transport task can be defined as a process whose purpose is to transport the set quantity of handled material within a defined time between the set loading and offloading locations. This determines the capacity of the conveyor as well as the route profile and layout, while the designer's job is to select the right belt speed and width and calculate basic operating parameters of the conveyor. This stage of the integrated computational design constitutes the initial calculation stage, mainly comprising calculations of the drive power and belt strength carried out using the basic method (Fig. 2).

(*) Tekst artykułu w polskiej wersji językowej dostępny w elektronicznym wydaniu kwartalnika na stronie ***www.ein.org.pl***

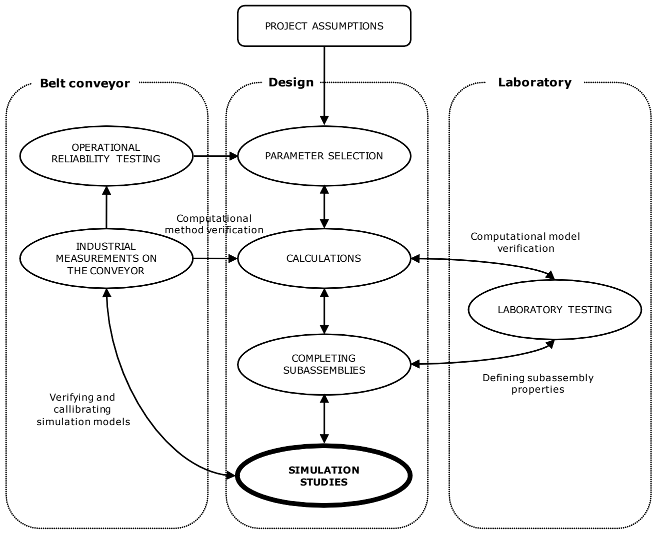

Fig. 1. The diagram presenting the place of simulation studies in the integrated design process of a belt conveyor [12]

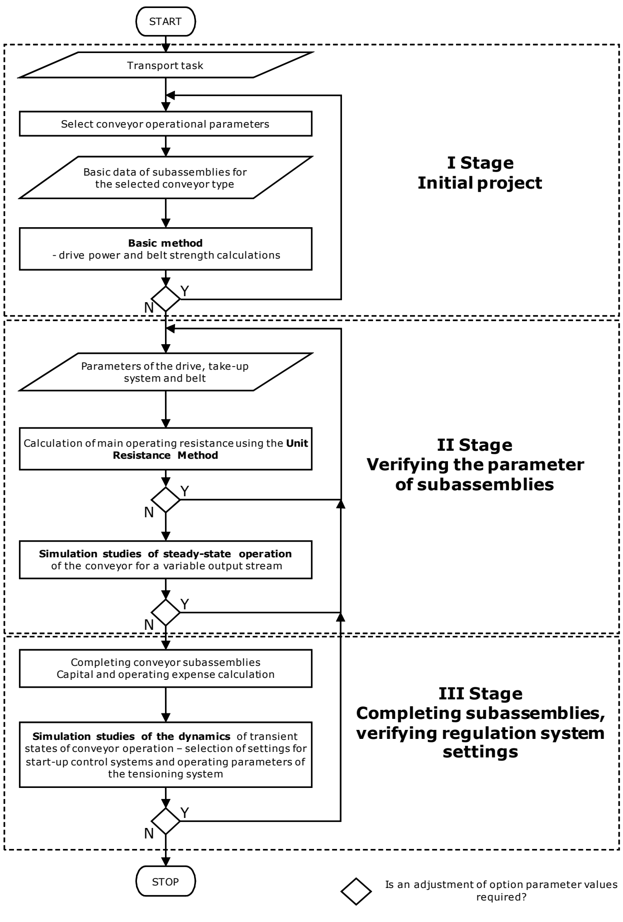

Fig. 2. Algorithm of belt conveyor design [12]

The next stage is to verify the selection of subassemblies: idlers, belt, driving and tensioning system. This stage should be supported by detailed calculations of main resistance of the belt using the Single Resistance Method [4]. This stage is concluded by simulation studies of the steady-state operation of the conveyor at variable capacities of loading points. The analyses cover the power consumption by the conveyor driving system, the belt loading state and its balance on curved sections of the conveyor route (Fig. 2).

The last, third stage of designing belt conveyors entails completing the subassemblies fitted to the conveyor and making an initial calculation of capital and operating expenses. At this stage the accuracy of the selection of subassemblies is finally verified by a process of simulation model studies of transient states of conveyor operation. The set-points of the start-up control system are adjusted and the operation of the tensioning device is analysed during conveyor start-up and breaking.

The diagram below shows the algorithm of the basic stages of the integrated process of designing belt conveyors (Fig. 2).

An important purpose of the simulation studies carried out at stages II and III of the integrated belt conveyor design is to analyse the belt tensioning system based on the results of calculations of the dynamics of transient operation states of the conveyor taking into account the rheological characteristics of the belt and the operating parameters of the drive control system.

The basic, widely used method for analysing the dynamics of transient states of conveyor belt operation is based on the assumption that all moving elements of the conveyor, i.e. those in translational motion like the transported material and the belt, and the rotating ones, i.e. the idlers and driving system subassemblies are concentrated in one point with a defined moving, moving with a constant acceleration or deceleration. In the case of a belt conveyor, this is too simplified, as due to the elastic properties of the belt not all moving elements of the conveyor are accelerated simultaneously. During the start-up, wave phenomena occur in the belt due to the profile of stress waves caused by the operation of drives and belt take-up systems. It does happen, particularly on very long conveyors, that the time delay between putting individual sections of the belt in motion ranges from several to tens of seconds. Thus calculation results produced using standard methods for assessing the dynamics of the start-up can be considered only approximate or preliminary for conducting more complex analytical procedures.

The problems associated with analysing the start-up of the conveyor and the operation of tensioning devices can be solved using a dynamic model of a belt conveyor with distributed parameters [8].

3. Dynamic belt conveyor model

In the conveyor model presented in Fig. 3, the reduced masses of drives, i.e. electric motors, couplings, gears and driving pulleys including the appropriate sections of the belt, the transported material and the reduced mass of the appropriate number of idlers were concentrated in the points where drives are installed. The reduced masses associated with the upper and lower belt were appropriately concentrated in centres of mass distributed along the conveyor route.

In the physical model devoted to analysing dynamic phenomena (Fig. 3), $\boldsymbol{x_i}$, represents the dislocations of individual points of the belt (i = 1, 2, ..., n). The resistance to belt motion along a given section of the conveyor is marked with $\boldsymbol{W_i}$ and it is assumed that the value and the sense of the resistance force depends on the belt speed $\boldsymbol{v_i}$. Depending on the formulated purpose of the model study, the value of resistances to motion is determined using standard methods [3, 17] or the single resistance method [4]. The components of the gravity force of the belt and the transported material placed on it, tangential to the direction of belt movement, are represented by $\boldsymbol{G_i}$, while $\boldsymbol{\delta_i}$ is the angle of slope relative to the modelled level of the $\boldsymbol{i}^{th}$ section of the belt. Active forces affecting the belt and coming from the drive are symbolised by $\boldsymbol{P_i}$ [8].

Due to rheological phenomena occurring in the belt during conveyor operation, belt models developed based on literature [13, 12, 19] were selected for analysing the uniaxial stress state. The selection of the belt rheology model depends on the purpose formulated for the simulation studies. If the analysis covers short-lasting, transient states of conveyor operation occurring during its start-up and breaking, the

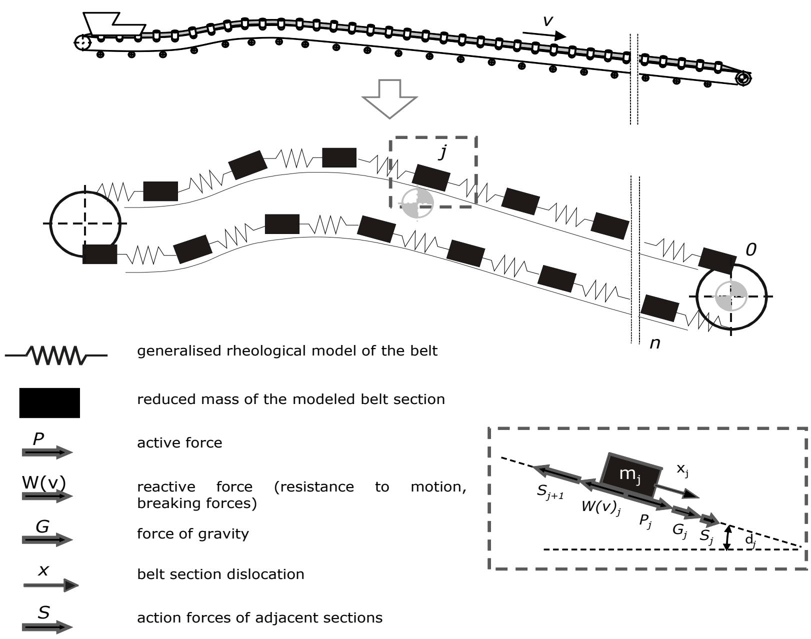

Fig. 3 The model for analysing dynamic phenomena in a conveyor belt [8]

two parameter Kelvin-Voigt model with a short stress relaxation time calibrated during simulation tests is sufficient. If the analysis concerns changes occurring during the steady-state operation of the conveyor with a variable load of handled material, it is necessary to use a standard model or a four-parameter one, which is a serial combination of two Kelvin-Voigt models [12].

The mathematical model of a belt conveyor is described by a system of second-order ordinary differential equations. Its matrix form is as follows [8]:

$$\mathbf{M}\cdot\ddot{x}(t)=\mathbf{N}\cdot\dot{x}(t)+\mathbf{K}\cdot x(t)+\mathbf{P}-\mathbf{W}+\mathbf{G} \quad (1)$$

where: **M** – reduced mass matrix;
N – damping coefficient matrix;
K – elasticity coefficient matrix;
W – resistance to motion matrix;
P – active force matrix;
x(t) – dislocation matrix;
G – matrix of component gravity forces.

Fig. 4 below presents a fragment of a block model of a conveyor with a two-parameter rheological model of the belt. The equation of motion of the j^{th} segment of this model is described by relationship (2), while its block diagram is shown in Fig. 5.

The method of modelling the driving force $\boldsymbol{P_i}$ depends on the type of the start-up system employed. For the purposes of the simulation studies conducted, a series of models were been developed of widely used drives described in the literature [12].

The equation of motion for the j^{th} segment of a conveyor with a two-parameter rheological model of the belt has the following form:

$$m_{zrj}\ddot{x}_j = S_j - W_j - S_{j-1} + G_j + P_j \quad (2)$$

where: S_j – sum total of elasticity and damping forces in the rheological model of the belt, [N];

$$S_j = k_j(x_{j+1}-x_j)+\eta_j(\dot{x}_{j+1}-\dot{x}_j) \quad (3)$$

where: k_j – elasticity coefficient of the belt rheological model, [N/m];
η_j – damping coefficient of the belt rheological model, [Ns/m];
x – dislocation of the segment, [m];

The belt tensioning system which ensures the correct alignment of the belt and the correct operation of the driving system forms one of the most important subassemblies of a belt conveyor.

The belt tensioning devices used can be divided into two groups:
- with a constant position of the tensioning drum during conveyor operation: rigid tensioning systems;
- with a changing position of the tensioning drum during conveyor operation: gravitational, hydraulic and follow-up belt tensioning systems.

Fig. 6 below presents the physical model of a gravitational tensioning system widely used in above-ground conveyors. Fig. 7, in turn, shows a model, simplified compared to the block diagram in Fig. 5, of a belt tensioning segment in a dynamic model of a conveyor.

The calculated value of the speed and dislocation of an additional belt point $\boldsymbol{x_d}$ is substituted in the differential equation system describing the conveyor model.

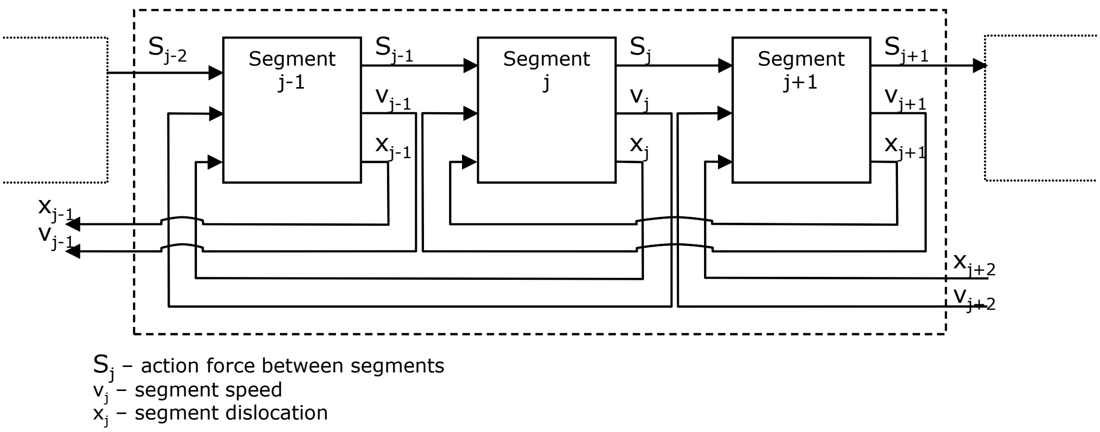

Fig. 4. The fragment of a block model of a conveyor [12]

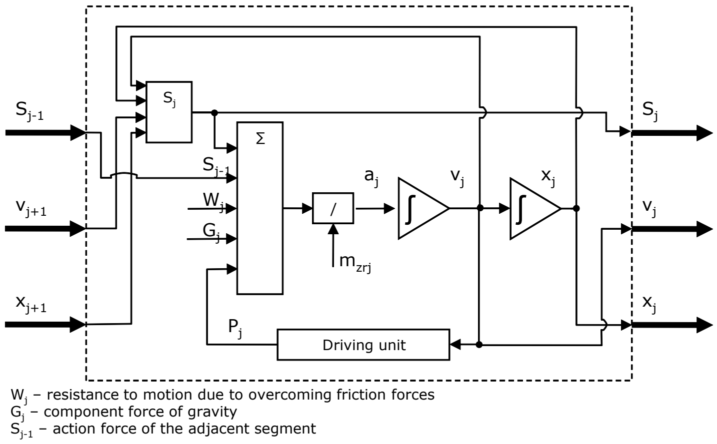

Fig. 5. A block model of a driving segment in the dynamic conveyor model [12]

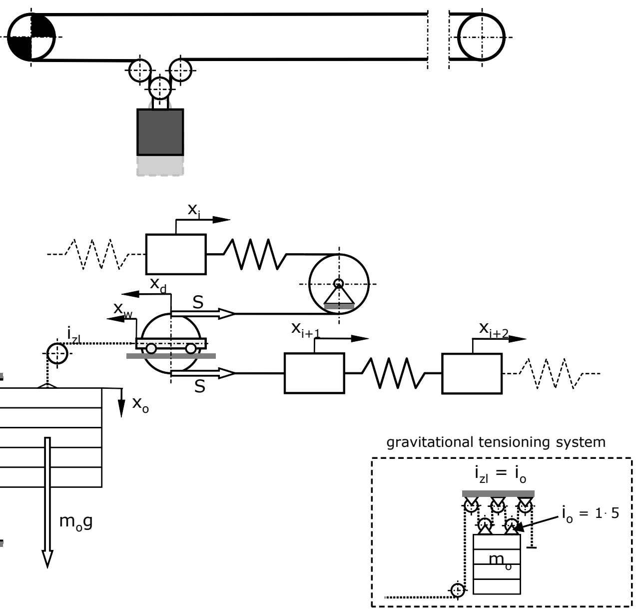

Fig. 6. The diagram and a physical model of a gravitational tensioning device [12]

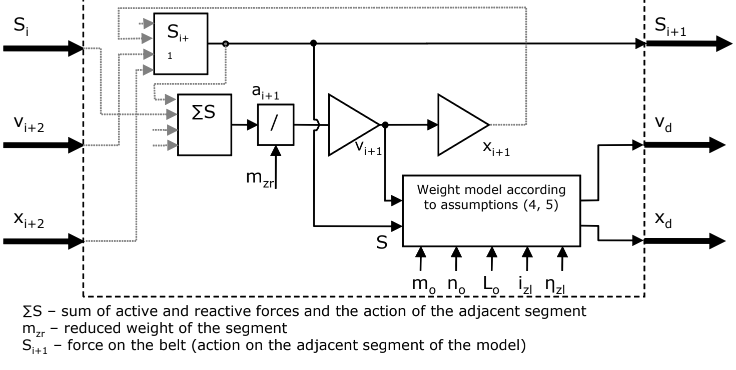

Fig. 7. Simplified block model of a gravity tensioning segment in the dynamic conveyor model

The acceleration of the weight is determined based on the following relationship:

$$a_o = \frac{2 \cdot S \cdot i_{zl} \cdot \eta_{zl}}{m_o \cdot n_o} - g \qquad [\text{m/s}^2] \qquad (4)$$

where: m_o – weight mass, [kg];
n_o – number of weights; [-];
S – force on the belt, [N];
i_{zl} – ratio of the tackle system, [-];
η_{zl} – tackle system efficiency $\eta_{zl} = f(v_o)$, [-];

After using an integration operation to determine the acceleration of the weight – $\boldsymbol{a_o}$, its dislocation – $\boldsymbol{x_o}$ and after accounting for the structural limitations of the length of the tensioning path $\boldsymbol{L_o}$, the value of the dislocation of the tensioning pulley is calculated. The calculation of this value accounts for the ratio of the tackle system and its efficiency, which varies depending on the speed of the weight $\boldsymbol{v_o}$. The value of the speed of the additional point $\boldsymbol{v_d}$ was determined from relationship (5).

$$v_d = v_{i+1} + 2v_w \qquad [\text{m/s}^2] \qquad (5)$$

where: v_d – additional point speed, [m/s];
v_w – tensioning cart speed, [m/s];
v_{i+1} – speed of the centre of gravity i+1, [m/s];

Operating parameters of a gravity-based tensioning system are adjusted using the number and the mass of weights and the tensioning path length.

Results of simulation studies of a conveyor with a winch and a gravity belt tensioning system verified against the results of industrial tests carried out at a copper ore mine [11] are presented below.

4. Verification of results from simulation studies of a discrete conveyor model with a gravity belt tensioning system

Simulation studies carried out using a discrete model of a conveyor made use of:

- the single resistance method (TT) to calculate the reactive forces of resistance to motion [4],
- a standard rheological model of the belt (3p) according to [13],
- a model of a gravity belt tensioning system;
- a model of the driving system with fluid start-up couplings;
- a variable sequence of motor start-up.

The list of selected parameters of processes and models of subassemblies adopted during simulation studies of the belt conveyor, simulation code: model3p-TT, is presented in publications [12, 13].

An analysis of results concerning changes of forces on the belt obtained by simulation studies of the discrete conveyor model (model3p-TT) and industrial tests (test) shows that the assumptions for building the model were formulated correctly. Values of the force ***S1*** obtained in model studies are greater than the measured value of the force ***STA***, which may be due to excluding the slippage of the belt on the drum actually occurring on the AB drum during all start-ups recorded (Fig. 8).

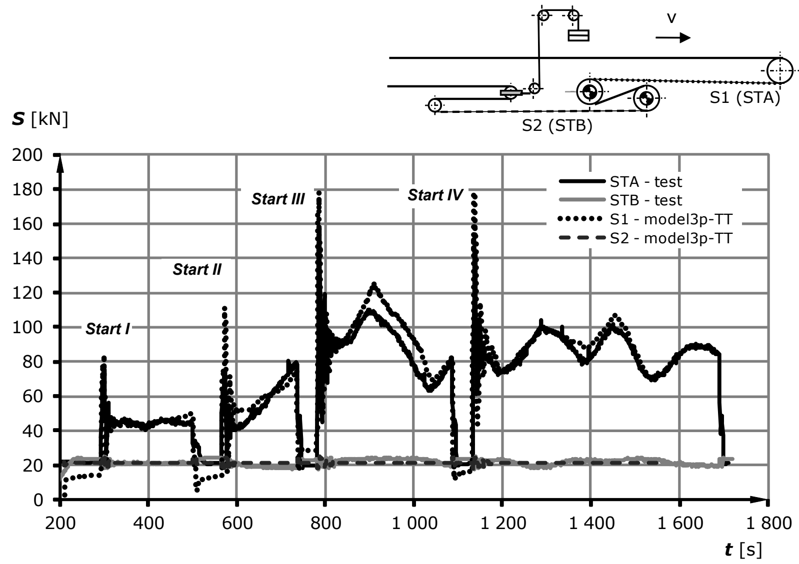

Fig. 8. Changes of forces on the belt of a conveyor during steady-state operation, start-up and breaking – industrial test (test) and simulation studies of a discrete conveyor model (model3p-TT) [13]

The verification of the discrete belt conveyor model mainly concerned transient states of operation, so Fig. 9 shows a comparison of results of industrial tests and simulation studies in the form of the dislocation of the tensioning pulley and the belt speed during conveyor start-ups I÷IV. During the recorded start-ups, the load of handled material on the conveyor varied [13], so the curves obtained by simulation studies can be considered satisfactory, and the adopted model of resistance to motion and the rheological model of the belt as correct. Apart from the possible errors in assessing the capacity of the conveyor, the inaccuracy of calculations of the drive power, the force on the belt and the length of the tensioning path may also be due to the approximate mapping of the conveyor route profile. Due to the lack of more precise survey information, the route of the conveyor was described using a single section with a constant slope, whereas the actual route of the conveyor consists of 2.5 m long segments founded on the floor of the mine pit. The variable slope angle of individual route sections in combination with a variable stream of handled material may significantly impact the momentary load on the drive.

The utility of results from simulation studies carried out using these models would be difficult to determine if

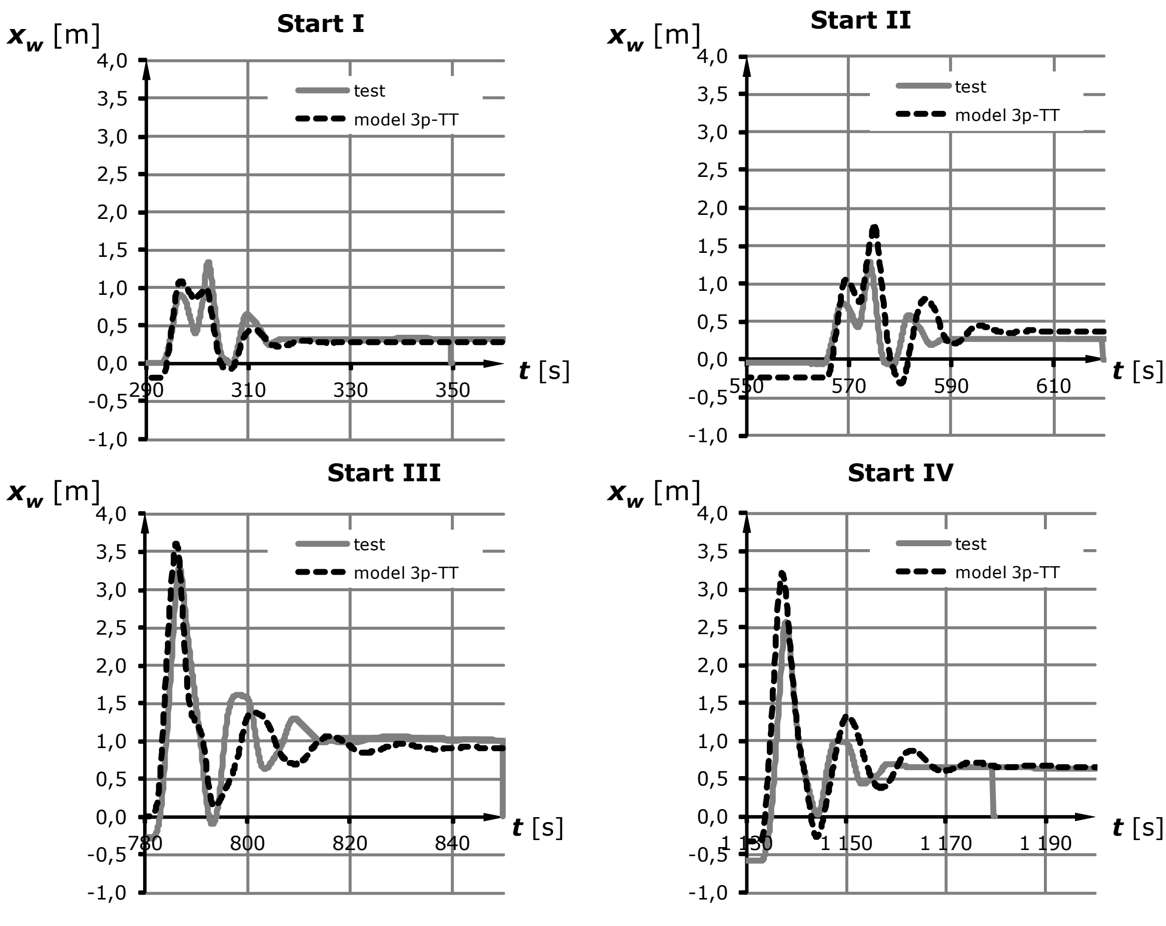

Fig. 9. The time-profile of changes in the dislocation of the tensioning pulley – a comparison of industrial test results (test) and simulation studies using a standard belt model (model 3p-TT) [13]

it were not for their verification at the operating site of the conveyor using a mobile measurement system. This system, constructed based on an original concept, together with the measurement apparatuses and the appropriate data processing procedures, has turned out to be completely suitable during measurements executed in industrial conditions, and the results obtained have painted a complete picture of the dynamics of transient operating conditions of the conveyor [11].

5. Summary

Designing a belt conveyor consists of executing a set of integrated processes to correctly select and combine its subassemblies into a unique machine meeting a defined transport requirement. This article presents simulation studies of conveyor operation as an indispensable, significant part of the integrated process of its design.

Simulation studies were executed using a dynamic model of a belt conveyor with distributed parameters, which includes models of belt tensioning devices as its integral parts. Their structure and place in the conveyor model was described using simplified block diagrams and equations [12]. The results of industrial tests of a belt conveyor conducted during its start-up, breaking and steady-state operation with a variable load of handled material were compared to the results of simulation studies on a belt conveyor model with a three-parameter rheological model of the belt [19] and a module for determining reaction forces based on unit resistances [4]. The driving system model used parameterized characteristics of fluid couplings determined on a VOITH test stand [9]. A comparison of the results obtained has shown that the discrete model of a belt conveyor with models of belt tensioning devices can be successfully used, with satisfactory accuracy, to simulate the start-up, breaking and continuous operation of a conveyor with a variable feed of transported material.

Simulation studies conducted during the design of a conveyor make it possible to select the appropriate subassemblies, optimum operating parameters and the correct set-points of regulation systems, thus significantly reducing future operational problems.

6. Literature

1. Advanced Conveyor Technologies Inc. Sidewinder. [online], 2011. http://www.actek.com/.
2. Conveyor Dynamic, Inc. Software: Beltstat, Beltflex, Beltcurv. [online], 2011. http://www.conveyor-dynamics.com/cdi_intro.htm.
3. Deutsches Instit. Normung. DIN 22101, Stetigfoerderer. Gurtfoerderer fur Schuttgutter, 2002.
4. Gładysiewicz L. Przenośniki taśmowe. Teoria i obliczenia. Oficyna Wydawnicza Politechniki Wrocławskiej, Wrocław, 2003.
5. Gładysiewicz L, Król R, Bukowski J. Eksperymentalne badania oporów ruchu przenośnika taśmowego. Eksploatacja i Niezawodnosc – Maintenance and Reliability 2011; 3: 17–25.
6. Hardygóra M, Komander H, Błażej R, Jurdziak L. Metoda prognozowania trwałości zmęczeniowej złączy wieloprzekładkowych taśm przenośnikowych. Eksploatacja i Niezawodnosc – Maintenance and Reliability 2012; 14(2):171–175.
7. Kacprzak M, Kulinowski P, Wędrychowicz D. Informatyczny system zarządzania procesem eksploatacji górniczych przenośników taśmowych. Eksploatacja i Niezawodnosc – Maintenance and Reliability 2011; 2: 81–93.
8. Kulinowski P. Badania modelowe nieustalonych stanów pracy przenośników taśmowych. Praca doktorska, Akademia Górniczo-Hutnicza, Kraków 1997.
9. Kulinowski P. Dynamic Start-up Calculations for Belt Conveyors with Measured Torque Curves of Fluid Couplings. Mine Planing and Equipment Selection 2004, A.A. Balkema Publishers, 2004; 443–448.
10. Kulinowski P. Informatyczne wspomaganie procesu projektowania przenośników taśmowych. Gospodarka Surowcami Mineralnymi, 2007; T.23, Z.4: 209–221.
11. Kulinowski P. Identyfikacja parametrów techniczno-ruchowych przenośników taśmowych z wykorzystaniem mobilnego systemu pomiarowego. Maszyny Górnicze, 2008; 3: 35–43.
12. Kulinowski P. Metodyka zintegrowanego projektowania górniczych przenośników taśmowych. Wydawnictwa AGH, 2012.
13. Kulinowski P, Zarzycki J, Furmanik K. Identyfikacja parametrów standardowego modelu reologicznego taśmy i jego wykorzystanie w symulacyjnych badaniach dynamiki przenośników taśmowych. Transport Przemysłowy i Maszyny Robocze 2012; 2: 3–8.
14. Kwaśniewski J. The use of monitoring to improve the raliability and endurance of continous coal handling systems. Archives of Mining Sciences, 2012 56(4): 651–664.
15. Mazurkiewicz D. Badania wydłużalności i wytrzymałości złączy klejonych w aspekcie opracowania komputerowego systemu monitorowania ich stanu w czasie pracy przenośnika taśmowego. Eksploatacja i Niezawodnosc – Maintenance and Reliability, 2010; 3(47): 34.
16. Overland Conveyor Company, Inc. Belt Analyst™. [online], 2011. http://www.overlandconveyor.com.
17. PN-M-46552:1993 Przenośniki taśmowe z krążnikami podpierającymi taśmę. Obliczanie mocy napędowej i sił napinających taśmę. Polski Komitet Normalizacji, Miar i Jakości. 1993.
18. Szybka J, Wędrychowicz D. Wyznaczanie strategii prewencyjnych odnów przenośników taśmowych. Materiały Szkoły Eksploatacji Podziemnej 2010, Kraków, 22–26 lutego 2010. Wydawnictwo IGSMiE PAN.
19. Zarzycki J. Wpływ własności reologicznych taśmy na parametry eksploatacyjne przenośnika. Praca doktorska, Akademia Górniczo-Hutnicza, 2011.

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