REVIEW OF THE DOCTORAL THESIS

prepared by mgr inż. Damian Bzinkowski, titled "Evaluation of the identification possibilities of the conveyor belt with the measurement system based on strain gauges" (*Ocena możliwości identyfikacji stanu taśmy przenośnika za pomocą tensometrycznego systemu pomiarowego*). The work was written under supervision of prof. dr hab. inż. Mirosław Rucki, Radom 2024, and consisted of 194 pages.

The belt conveyors belong to the widely used transport means in various branches of industry. The real-time monitoring of their work allows for improved safety and prevention of failures, which are important arguments for undertaking the research efforts. Moreover, predicted and prevented failures substantially reduce the overall production costs. In his Thesis, MSc. Eng. Bzinkowski rightly emphasized that the exchange of the belt after its damage during work significantly increase the expenses compared to the cost of the planned maintenance and exchange (page 38). Thus, any effort directed to the failure prevention, is economically rational one. The Author cites in his dissertation the available data concerning the market expenses spent on the monitoring systems for the conveyors (page 16). These reached ca. $200 millions in 2018, with predicted increase up to $250 billion in 2024.

Introduction of the monitoring systems and the predictive maintenance of the belt conveyors is a necessary condition for re-orientation of the industry to the smart factory direction, conforming the requirements of sustainable development set among the European Union priorities. Correct identification of the belt damage type and its early detection provide ground for timely regeneration, which is very important from both the economical perspective and the circular economy priorities, including environmental protection. Hence, the present Doctoral Thesis deals with very rich and important branch of knowledge from the area of engineering sciences, belonging to the discipline of Mechanical Engineering.

1. The title, research problem, and methods

The Thesis presented by MSc. Eng. Damian Bzinkowski consists of the title page, table of content (pages 7-8), abstracts in Polish and English (pages 9-10), list of abbreviations and nomenclature (page 11-14), Introduction being section 1 (pages 15-16), five chapters (pages 17-188), and list of references (pages 189-194). The second chapter contains formulation of the objectives and the description of the scope of the work, while the last chapter 6 presents the summary and conclusions. The structure of the work is correct, and the title "Evaluation of the identification possibilities of the conveyor belt with the measurement system based on strain gauges" (*Ocena możliwości identyfikacji stanu taśmy przenośnika za pomocą tensometrycznego systemu pomiarowego*) corresponds to the content of the work and clearly indicates the author's intentions and plans.

When presenting the actual state-of-art and the available solutions, the Author noted that the belt is the most critical and expensive element of the belt conveyor (page 28). The large number of published scientific papers, however, describes the systems for monitoring of other conveyor elements, often drive units, engines, gear motors and their components, e.g. bearings and gear wheels. Compared to the total number of publications on the conveyors operation monitoring, the number of works devoted to the systems for the real-time belt monitoring is small, which indicates the importance of the knowledge collected and presented in dissertation.

In Chapter 2, the scientific thesis was formulated, "During the transport process, the conveyor belt exerts different pressures on the conveyor drum, depending on the load and damage, which can be identified using a strain gauge-based measurement system" (page 18). In the reviewer's opinion, the formulation of the thesis is correct and includes significant innovative elements. Noteworthy, the strain gauge-based measurement system was registered

in the Patent Office of Republic Poland (patent application No. P.447569). Earlier, in the beginning of Chapter 2 (page 17), Author formulated clearly and precisely the respective scientific goal, corresponding to the thesis, and three auxiliary theses were also adopted to prove the main one (page 18). The subsequent chapters of the work refer directly to the theses, consistently lead to the utilitarian goal, which is, as stated in the thesis, "the development of an innovative system for monitoring the operation of the conveyor belt at low costs, increasing the safety of the conveyor operation and preventing failures" (page 18). The scope of work carried out in frames of the dissertation was defined correctly, in a way that allows achieving the goals and proving the auxiliary theses and the main one.

From the methodological perspective, the presented work deserves the highest rating. Apart from the literature analysis with comprehensive presentation of the relevant scientific knowledge on the topic, the series of experimental results are presented. The experimental data was used for the analysis matching the registered real-time signal with the actual state of the belt. In the research, three experimental rigs were used: one for the measurement of the belt strength, one for the modeling of the conveyor belt work without load, under load, and with preset damages, and one for calibration of the strain gauges. The latter was originally projected and built by the Author and served for calibration for the strain gauges placed on the drum surface, i.e. in their real work conditions. The calibration was performed according to the international standards and recommendations, and the measurement uncertainty and repeatability was estimated accordingly. The research program is presented schematically with detailed description for each registered run of the conveyor belt. Individual areas in the signal graphs were indicated, related to the parameters typical for a given experiment, such as belt speed, load or damage.

Very interesting and important from the perspective of further development of the proposed system appeared to be the attempt of Artificial Intelligence application to the analysis of the registered signal, described in subsection 5.3. The results were processed with five different machine learning algorithms for the loaded belt, and 32 more algorithms for the belt with preset damages. Several of the algorithms were demonstrated to be able to identify certain damage and load. These results can be treated as the preliminary insight, which can be further used in the research and development of the proposed innovative system.

2. Formal evaluation

2.1. Sources and experiments

The reference list consists of 103 titles, including 7 actual ISO standards and 15 websites with the catalogue data or research reports. The sources are representative and corresponding to the work objectives. Thus, it can be stated that the Author possesses the necessary skills to work with the literature of the subject, is able to accurately identify and correctly use sources in both Polish and English, refers to industry standards and skillfully combines industrial problems with scientific solutions.

The research object, namely conveyor belt with the innovative monitoring system, is described in detail in the separate subsection 4.1 (pages 55-59). The research plan is clearly presented in form of a flow chart (Fig. 4.8, page 63). Research methodology does not raise any objections. The experimental rigs used in the work fully correspond to the formulated goals, experimental research methods and metrological analysis were selected and carried out appropriately. Number of 2000 of repetitions during the calibration process (page 80) enables in-depth statistical analysis of the registered signals. For each angle position, 10 repetitions were made, providing the solid background for repeatability estimation. Metrological characteristics of the strain gauge system proved that the measurement accuracy is sufficient for the designed purpose and allows for registration of reliable data for further analysis. The original construction of the calibration rig is noteworthy, since it ensures minimization of the influencing factors.

After the description of the measurement system, the experiments are presented in the dissertation, including static and dynamic tests of the belt in the conditions, modeling the work of the belt conveyor. Subsequent subsections 5.2.1-5.2.3 contain the results and discussion concerning the tension of the belt in static state, pressure on the strain gauges during the movement of the loaded and unloaded belt, as well as the movement of the belt with preset damages in form of different cuts. Each measurement was repeated several times to collect data for the statistical analysis and generalization. Considering the sampling frequency, amount of the collected data can be qualified as *Big data*. However, some methodological doubts can be raised due to lack of a systematic approach in the damage sequence design. Nevertheless, keeping in mind the preliminary and exploratory nature of the research, considering also limitations of the doctoral dissertation, this remark should be treated rather as recommendation for future research program. Indeed, important addition to the analysis of the damaged belt states is presented in subsection 5.2.4 in form of the belt material strength tests.

The next stage of the research intended to reach the dissertation goals was the analysis of the registered data and initial assessment of the possibility to apply a machine learning to the process. The author's skills deserve high praise, since he exploited the capabilities of the software *Classification Lerner* in MatLab environment to the identification of the actual belt state. Moreover, he used the program *Diagnostic Feature Designer* to evaluate, which feature of the collected data was the most important from the perspective of machine learning procedures.

Both measurement methods and the subsequent data processing were chosen and applied correctly, according to methodology of scientific research. The performed analysis ensured the scientific reliability of the conclusions drawn.

2.2. Structure of the dissertation

Composition of the dissertation can be evaluated positively since it is transparent and functional, reflecting the intentions and plans with consistent presentation of the subsequent research stages, analyses and conclusions. After the short introduction, the main and auxiliary theses are formulated, as well as objectives of the work. Next, the actual state-of-art is discussed, presenting classifications of the conveyors, belt types, issues with maintenance and repair costs, safety issues, and a range of the contemporary monitoring systems for belt conveyors in the subsequent subsections.

After the theoretic introduction, experimental sections are placed. First, the tested belt is described, experimental plans and measurement rigs are presented. Next, the experimental results are described and discussed. Results are given in a transparent way, according to the experimental research plan presented in subsection 4.2. Unfortunately, perception of the results is somewhat difficult due to the large number of the measurements and repetitions, graphs of the registered signal, and their detailed descriptions. The experiments were repeated for different belt speeds, different loads, and different preset damages. Nevertheless, the description itself presents important knowledge, since it explains, which features of the registered signals are related directly to the actually identified state of the working belt.

In the subsection 5.3, initial attempts of the AI application for the collected signals analysis are described. To the same registered signal sequences, different machine learning algorithms were applied providing different results. In some cases, it was possible to reach 100% of identification of the observed features, loads or damages. These initial results supported the conclusions drawn from the previous analysis that the innovative system can be used for real-time monitoring of the working conveyor belt. The conclusions, both scientific and utilitarian ones, together with the description of the advantages of the tested system and recommendations for further research and applications, were placed in a separate, sixth chapter of the dissertation.

The abovementioned structure of the work is logical, and it corresponds with the formulated goals and the chosen research methodology. It should be emphasized that the description of each research stage was concluded with reference to the relevant auxiliary thesis or respective research objective. Such a reference makes it easy to follow the logic of the work with scientific reasoning, leading to the main goal step by step, according to the planned methods and research program.

2.3. Terminology

The scientific terminology used in the dissertation is correct and consistent and corresponds with the standards of the Mechanical Engineering discipline. Nomenclature used in the equations is consistent with the references cited and the branch standards.

3. Scientific content assessment

The evaluation of the dissertation from the scientific perspective is positive. The Author undertook very difficult task to build an innovative measurement system, to perform calibration and to assess its metrological characteristics, such as uncertainty and repeatability, and to carry out detailed analysis of the acquired signal. The author's attempt to use the machine learning algorithms deserves special attention as it provides further arguments in favor of continuing the research towards industrial implementation. The strain gauges-based measurement system registered in the patent office is an innovative solution, and its investigation provides new valuable knowledge to the scientific discipline Mechanical Engineering. The scientific value of the dissertation is confirmed by four research papers, one of them published in cooperation with foreign co-authors. Initial interest expressed by the research centers in Italy, Serbia, and Lithuania indicates international significance of the performed research and presented results.

The dissertation proves the ability of applicant MSc. Eng. Damian Bzinkowski to solve both engineering problems and scientific ones, to find additional ways for the data analysis, and to apply the most contemporary tools like Artificial Intelligence. Experiment planning is methodologically correct, metrological analysis is consistent with the common standards and recommendations, and scientific reasoning corresponds with the best practices of engineering sciences.

The dissertation provides important experimental results on the state of the conveyor belt in different work conditions. It demonstrates that the registered signal is directly dependent on the load or damage of the belt. Another important practical aspect is related to the possibility of real-time damage detection, both surface cuts and the ones cutting through the entire material. Collection and registering of large amount of data for actual monitoring and further detailed analysis opens wide possibilities for future research in line with the general concept of *Industry 4.0*.

The abovementioned points indicate high scientific value of the dissertation.

4. Critical remarks

The dissertation is well designed and prepared, with only sporadic shortcomings and deficiencies. Author did not manage to avoid incomprehensible shortcuts and chaotic sentences, too long and difficult to understand. For instance, in page 38, "Rosnący popyt na surowce mineralne pojawiające się nieplanowane przerwy w transporcie materiałów wynikające z awariami taśm mogą spowodować znaczne straty produkcyjne, często niemożliwe do zredukowania podczas ciągłej całodobowej pracy przez siedem dni w tygodniu (Błażej i in., 2022)".

There are also shortcoming of formal edition, e.g. lack of the comma at the end of a point in page 11, the following line:

"$K(t)$ – kosztów zakupu oraz naprawy taśmy na przenośniku na jednostkę czasu."

It can be considered unfortunate idea to describe the strength of the tested belt twice: first in subsection 4.1 in general terms, and then with experimental results in subsection 5.2.4.

In the reference list, I did not find the position *Evaluation of measurement data — Guide to the expression of uncertainty in measurement* JCGM 100:2008, which is cited at least 6 times in the work.

In terms of experiment planning, the lack of a systematic approach to a sequence of damages to be identified during tests deserves criticism. It seems that performing a series of measurements after applying a subsequent single damage would provide a more complete picture of the impact of damages on the registered signal pattern and the possibility of their identification.

It should be noted, however, that these remarks do not decrease the value of the scientific content presented in the dissertation. Both state-of-art presentation based on the available publications, and the original research program, results and analysis are highly valuable and represent significant achievement.

5. The questions to the Applicant

After analysis of the presented dissertation, some question can be asked. In particular:

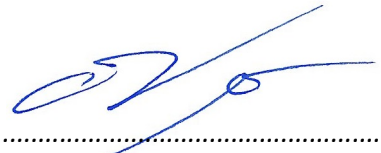
- During calibration, from the very large number of repetitions, impact of the angle position on the indications of the strain gauge placed on the drum surface was determined with high repeatability. Please explain, is it possible to treat this feature as a systematic error and hence to eliminate it, to compensate, or to make a relevant correction?

- Is it possible, in opinion of Applicant, to undertake an attempt of creation a digital model of the real-time conveyor belt work like a *Digital twin* system, based on the collected data?

6. Conclusions

The final assessment of the work, both in formal and substantive terms, is positive. The innovative aspects of the proposed engineering solution should be highly emphasized, along with the correctly formulated theses, properly planned and performed experiments, comprehensive analysis of the data obtained and appropriately drawn scientific and utilitarian conclusions. Applicant demonstrated his skills in literature analysis and experiment planning and performing. In particular, his ability to apply Artificial Intelligence tools accordingly to the work objectives is appreciated. On this basis I conclude that both formal and substantive aspects of the reviewed dissertation by MSc. Eng. Damian Bzinkowski titled “Evaluation of the identification possibilities of the conveyor belt with the measurement system based on strain gauges” (*Ocena możliwości identyfikacji stanu taśmy przenośnika za pomocą tensometrycznego systemu pomiarowego*) meets the high requirements of the doctoral theses in the scientific discipline Mechanical Engineering. For that reason I apply for admission MSc. Eng. Damian Bzinkowski to the subsequent stages of doctoral procedure.

Ostrava, 3.08.2024



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