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Review of the doctoral thesis

DIAGNOSTIC SYSTEM FOR LOW-SPEED BEARINGS

Dipl. - Ing. Michael Oeljeklaus

Based on the request (ref. no. TUL-378790/2112) of prof. Dr. Ing. Petr LENFELD, dean of FE TUL, I developed this opponent review on the above-mentioned dissertation thesis.

The doctoral thesis by Michael Oeljeklaus focuses on the problems of diagnostic systems of low-speed bearings. The work is divided into 9 chapters and is written on 126 pages including a list of used literature and a list of his own publications.

The doctoral thesis starts with a research of published articles and patents, which contain some principles of the diagnostic systems of low-speed bearings. It is summarized that mostly measurements of vibration and noise are used for these purposes. The aim of the doctoral thesis is a proposal and design of a diagnostic system for low-speed bearings that are used in a concrete example of a chain conveyor in the paint shop of company Škoda Auto a. s. Mladá Boleslav. This is defined in detail in chapter 3. In the next two chapters, there is described a current state of the sprocket shaft bearing assembly including the calculation of shaft stress and deformation by bending. Chapter 6 pays attention to an analogy of roller bearings and planetary gear kinematics. There are calculated angular velocities of different bearing parts and the results are used to the determination of the frequencies in measured vibration spectrum on the bearings corresponding to the damages of bearing parts. The next chapter presents the main result of the doctoral thesis. There is proposed a principle of the later designed diagnostic system of low-speed bearings using the reference element between two pairs of roller bearings. This part has one degree of freedom and presents a base for obtaining information about damages of roller bearings. One possibility consists in the driving of the reference element by higher revolutions and at the same time measuring the bearing vibration. In the frequency spectrum, there can be found amplitudes that are connected to damages of bearing. The second possibility consists in the indication of a higher resistance by the moving of the reference element. This solution was patented. The diagnostic

system uses a planetary gear to driving of the reference element and by the resistance increase of some bearing in the shaft assembly the sun gear is brought into move. In chapter 8 there is presented a design of the diagnostic device for low-speed bearings for the sprocket shaft bearing assembly in the chain conveyor of the paint shop in the company Škoda Auto a. s. Mladá Boleslav.

There are proposed three variants and one of them was designed in detail. Complex process contains stress and deformation calculations and many structural features. The parting of the whole shaft assembly in two subassemblies - sprocket side and bearings side - has an advantageous effect. This solution makes the maintenance easier. Two prototypes of the diagnostic system were produced and the function and strength were verified in the laboratory. One of the prototypes of the sprocket shaft bearing assembly was used in the chain conveyor of the paint shop in the company Škoda Auto a. s. Mladá Boleslav.

The doctoral thesis is written logically and clearly in good English but the use of possessive apostrophes for non-life objects is questionable (if there is missing one by lively "authors" on page 125). There is used German language without any translation into English in the Tab.6.1. The same in figures 9.5 and 9.7 (Czech language). The calculations - strengths and the kinematics - of the designed parts of the diagnostic systems of the sprocket shaft bearings assembly are carried out correctly in analytical and numerical ways. The basic subject of the doctoral thesis is a patented diagnostic system based on the reference element.

The doctoral thesis is written on the appropriate technical level and fulfills demands set for the doctoral thesis in the field of technical sciences. The candidate for the doctor's degree demonstrated very good knowledge and high abilities for solutions of difficult design projects.

Questions to the doctoral thesis:

1. Could uneven rotation of driven sprockets affect the diagnosis (influence of chain drive kinematics)?
2. How to accurately determine a chain drive transmission error?
3. Could you explain how the damping effect is achieved (fig. 4.7)?
4. Why are you talking about the "shaft" when it is not subjected to torque?

After my review, according to law no. 111/1998 Coll. Section 47, I can recommend the doctoral thesis of Michael Oeljeklaus for defence, and after a successful defence to grant to Michael Oeljeklaus Ph.D. degree "Doctor".

In Ostrava 8.4.2019

Prof. Dr. Ing. Miloš Němček

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Review of the doctoral thesis

DIAGNOSTIC SYSTEM FOR LOW-SPEED BEARINGS

Dipl. - Ing. Michael Oeljeklaus

Study programme: P2302 – Machines and Equipment
Study branch: 2302V010 – Machine and Equipment Design

This review of the doctoral thesis was carried out on base of the request of prof. Dr. Ing. Petr LENFELD, dean of the Faculty of Mechanical Engineering of the Technical University of Liberec.

a) Analysis of the doctoral thesis

The doctoral thesis is written on 126 pages and is divided into ten chapters including introduction and conclusion. Chapter 1 is focused on the introduction into problems of the low-speed bearings diagnostics. There is emphasized the importance of the effective diagnostic system that can be used in the modern production of Industry 4.0. Chapter 2 contains a relative broad research in this field. There are described the same methods which are based on the measurement of vibration or noise. All these systems are verified with good results in the laboratory conditions. Disadvantages appear in the production processes, where the vibrations corresponding to damages of the low-speed bearing are suppressed by vibration and noise of the production machines. Chapter 3 defines the aim of the thesis and solution methods. The main task is the diagnostics of low-speed bearings by the sprocket shaft bearing assembly including the design of the system, prototype production, verification under load and installation of the assembly in the chain conveyor at the ŠKODA AUTO a.s. paint shop in Mladá Boleslav.

In chapters 4 and 5, there is described an actual state of the chain conveyor and the sprocket shaft bearing assembly. There are executed its strength calculations and obtained information about deformations and stresses in the parts of the sprocket shaft bearing assembly, especially of the shaft. The main results of these calculations are

verified by laboratory tests. In chapter 6, there are presented kinematic behaviors of the roller bearing based on the Willis´s method of angular velocities calculation. There is shown kinematic analogy between rolling – element bearings and planetary gear systems and the way to determine vibration frequencies which have coherences with damages of roller bearing parts. The fundamental result of the doctoral thesis is presented

in chapter 7. There is designed an original diagnostic system of low – speed bearings. The system is based on the reference element. In this design case, the low-speed sprocket shaft is mounted using two pairs of roller bearings. The two shaft bearings are seated within a reference element, and the reference element itself is mounted in the frame using further two frame bearings. The reference element has one degree of freedom and can be rotated by means of a drive, for example, a belt drive, by high revolutions. This system gives a possibility to measure vibrations, which correspond to damages of bearings very effectively. The analogy of roller bearings and the planetary gears is shown in the new system, too. In chapter 7, there is also presented another system of diagnostics based on identifying increased rolling resistance. In this case, there are calculated forces and moments which can be used for the detection of damages of shaft or frame bearings of the sprocket shaft bearing assembly. These two original diagnostic systems are in a patent proceedings.

In chapter 8, there is presented a design of the diagnostic system that is chosen as an optimal solution of more variants. The main criterions in this decision are strength and easy maintenance of the sprocket shaft bearing assembly. In chapter 9, there are laboratory tests of the diagnostic device. There were used two prototypes, one of which only for the strength test and the other one only for the diagnostic testing. The second prototype was mounted in the chain conveyor and it is used in the pre-treatment line at the ŠKODA AUTO a.s. paint shop in Mladá Boleslav.

b) Objectives

In the doctoral thesis the main objectives of the research were:

- Design of the original and patented solutions of the diagnostic system.
- Theoretical basis for the vibration frequency identification corresponding to damages of low-speed bearings parts.
- Complexity of the solution based on the actual state of research, analysis of current state of the low-speed bearings diagnostics, design of original system, its production, laboratory testing and application in operating conditions.

In my opinion, it can be stated that all the objectives of this doctoral thesis have been met successfully.

c) Theoretical benefits of doctoral thesis

Two new methods of low-speed bearings diagnostics based

- in the first case, according to the kinematic state of the system with the reference element with one degree of freedom, as a part of the sprocket shaft bearing assembly, there can be identified damages of low-speed bearings in the vibration spectrum,
- in the second case, there is shown a way to the calculation forces and moments in the original diagnostic system using the planetary gear, and on this basis damages of low-speed bearings are detected.

d) Practical benefits of doctoral thesis

- In the frame of doctoral thesis, there were proposed and designed two diagnostic systems for the sprocket shaft bearing assembly. One of them was produced and two prototypes were tested in the laboratory.
- After the verifying of the diagnostic and functional reliability, one prototype was installed in the chain conveyor and is used in the pre-treatment line at the ŠKODA AUTO a.s. paint shop in Mladá Boleslav.

e) Suitability of methods of solutions

The doctoral thesis has a logical structure based on the background research, describing the actual state of the problem field, theoretical calculations of important parts strenght with using of FEM, submission and design of diagnostic system, production of prototypes, testing in labotatory, verifying of the functional reliability and application in the real conditions in the industry. By these tasks, modern computational methods and measuring equipment were used.

f) Comments to the results and originality of the practical benefits of work

The main results of the doctoral thesis are two original diagnostic systems. The principle was patented in the Czech Republic and in Europe. This system was produced at the ŠKODA AUTO a.s. Mladá Boleslav and used in the pretreatment line paint shop.

g) Formal level of work

Formally, the work is processed on a good technical level. It is structured logically, and the text is written in the excellent English language clearly and intelligibly. Only in one table, there was used German in original dates from the German publication.

h) Evaluation of publications

The Ph.D. student presents 4 articles on the international conferences and he is the main author of two patents which are related to the diagnostics of low-speed bearing.

Comments and questions to work for defense

Formal issues:

I have found no essential or formal mistakes. The doctoral thesis is written in very good English. Its level and results are in accordance to the usually required grade and deserves a very positive evaluation.

Questions for the defense:

1. Could you compare production and maintenance costs of the current diagnostic system in the paint shop of the company ŠKODA AUTO a. s. and the costs of the new system designed by you?
2. What is the necessary accuracy of the manufacture of the diagnostic system with planetary gear?

Concluding expression of opinion

I can state that all the objectives of the doctoral thesis have been fulfilled. On the base of the review described above, according to law no. 111/1998 Coll. Section 47, I can recommend doctoral thesis of Michael Oeljeklaus for defense, and after a successful defense to grant Michael Oeljeklaus Ph.D. degree "Doctor".

In Prague 31. 3. 2019

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Review of the dissertation

Michael Oeljeklaus

with the title

„DIAGNOSTIC SYSTEM FOR LOW - SPEED BEARINGS"

Study branch: 2302V010 – Machine and Equipment Design

University: Technical University of Liberec (TUL), Faculty of Mechanical Engineering

Analysis of work

Dissertation (the DisP) focuses on the highly topical issue of diagnosing low-speed bearings running directly during the operation of the technical system and its necessity also result from the urgent demands of the industry on solutions to specific problems associated with this type of diagnosis. In practice, there is currently no reliable method to reliably predict damage to such machine parts in state-of-the-art production systems. It is therefore a problem area in ensuring continuous and reliable production on production lines, i.e. without production failures caused by unexpected failures and their subsequent removal. Given the negative experience with low speed bearings on production lines and the resulting considerable financial losses, this DisP and the findings and conclusions put forward for technical practice are of great importance.

DisP is divided into the following chapters

- **Introduction** – In the introduction, the author comments on what is the subject of DisP and states that in practice, low speed bearings are used in transport systems, but also in the manufacture of machinery and systems using production technology closely associated with the transport of materials or processed products. In large industrial plants, production is currently predominantly carried out by a number of robots and complex production lines, which include a high level of automation and computer control. These lines often operate without human intervention and the complex manufacturing process is controlled by monitoring systems. A fully automated predictive diagnostics of machines and their components has thus become an integral part of industrial production. In DisP, the author focuses primarily on the design of operational diagnostics for chain conveyors, especially for monitoring and predicting operational damage to low-speed bearings.
- **Research** – In this chapter, the author conducts a literature and patent search on low-speed bearings. It shows the direction of research and introduces the reader to several methods proposed by individual authors for predicting life, diagnostics and behaviour monitoring of these bearings. Most of these methods are based on acoustic signal analysis or bearing vibration measurements. Mostly, however, the mentioned methods are not suitable for carrying out bearing diagnostics without interrupting the production line operation, or are suitable for use up to a higher speed than required or with low bearing loads.
- **Aim of thesis and processing methods** – Here are the goals of DisP. The main objective of this work was to design and develop a diagnostic system for low-speed ball and roller bearings, with a special focus on bearing assemblies used in chain conveyors. Other results of this work include stress analysis part of the bearing assembly of sprocket shaft, prototyping, verification of the functionality of the diagnostic system in laboratory conditions, load measurement and implementation of the final prototype for a chain conveyor operated in the paint shop ŠKODA AUTO a. s. in Mladá Boleslav.
- **Low-speed bearings in conveyor systems** – In this chapter, the author focuses on the analysis of kinematic ratios and load cases for conveyors operated in paint shops of manufacturing companies. It

describes the individual arrangement of the conveyor drive and the location of the drive units and the design of the sprocket shaft mounting.

- **Strength of the current sprocket shaft bearing assembly** – The author states that in order to design a diagnostic device for low-speed ball and roller bearings, it is necessary to determine the strength ratios of the shaft type (sprocket support shaft). The results obtained are then used as criteria for selecting an optimized variant from the proposed solutions.
- **Diagnosing damage in ball and roller bearings** – In this chapter, the author focuses on the principle of ball and roller bearing diagnostics and bases it on the definition of kinematic conditions of individual bearing components.
- **Diagnostic device for low-speed ball and roller bearings** – In this chapter, the author states that two principles for the low speed ball and roller bearing diagnostics have been developed and implemented. In both cases, the organ structure of the device consists of a reference element and two pairs of bearings. In the first case the damage of the bearing or bearing part is detected by the vibration measurements and in the latter case by detecting increased rolling resistance.
- **Design of the diagnostic device for low-speed bearings** – In this chapter, the author suggests designing three design options for a diagnostic device. It compares and selects individual variants for specified requirements the best option, which then optimizes from the point of view of minimizing deformations and stresses and proposes shape, space and position optimization of individual machine parts.
- **Laboratory test of the diagnostic device** – In this chapter, the author states that two prototype diagnostic devices have been produced. The first prototype was tested for fatigue and subsequently subjected to maximum load. A second prototype with a monitoring unit was used to verify the diagnostic capabilities of the device. In both cases, the shaft was driven by a gearbox with an electric motor.
- **Conclusion** – At the end of the work, the author comments on the achieved results and summarizes the individual findings related to the newly proposed monitoring equipment in DisP.

Achieving the goals set in the DisP

The main objective of this work was to design and develop a diagnostic system for low-speed ball and roller bearings, with a special focus on bearing assemblies used in chain conveyors. The resulting diagnostic system was mounted on a chain conveyor installed in the ŠKODA AUTO a.s. in Mladá Boleslav and is actually operated since 2018.

The objectives and sub-objectives of the doctoral thesis I find it fulfilled.

Level analysis of the current situation in DisP solved problems

The analysis of the current state of the solved issue is presented in the proposed DisP in an understandable and, in my opinion, exhaustive way. Unfortunately, according to the author, in practice there is currently no reliable method that can reliably predict damage to low-speed bearings in state-of-the-art production systems directly during their operation. Despite the aforementioned, the author in DisP has several methods developed and proposed by some authors for the diagnosis of low-speed bearings listed and analysed from the point of view of their suitability for achieving the DisP of the specified targets.

Theoretical contribution of the dissertation

The main theoretical contribution of this DisP is that, based on the analytical description of the operating conditions of the chain conveyor, two different concepts for low-speed bearing running diagnostics have been developed. The basic idea behind these solutions was to introduce a reference element into the shaft bearing assembly on which the sprocket is mounted. First, it is possible to rotate the reference element at high speed and to measure the vibration that occurs due to bearing damage. Second, if the bearings are undamaged, the reference element must be able to rotate freely and without resistance. If the resistance moment increases, it means that one of the bearings is damaged. In the DisP this second proposal is elaborated in more detail, as this method of diagnosis is considerably simpler in terms of design and lower costs of its implementation and deployment are expected. The theoretical contribution of the thesis also includes the design of three variants of monitoring units based on the principle of planetary gearbox, their mutual evaluation and optimization (especially the shape optimization of structural elements and spatial arrangement of machine parts) of the selected variant.

Practical contribution of dissertation

The practical benefit of DisP is the physical realization of the monitoring unit, which is based on the detection of an increase in the resistance torque that has been patented. Also practical is the design of the system that makes it simple removing the bearing unit and hence its rapid replacement by a new one. The damaged unit is then repaired in areas designated to act. The monitoring unit has been tested under laboratory conditions for loading and fatigue life. Its diagnostic capabilities have also been tested for failure of one or the other set of bearings. After successful test results, the resulting design solution was installed in the mid-2018 in the ŠKODA AUTO a.s. and put into operation.

How the methods have been applied

The chosen methods were applied appropriately and correctly in relation to the logic of the device development process designed for the operational diagnostics of low-speed bearings, its design, design of applied computational models, etc.

Proving of relevant knowledge in the field

I think that the author is very well oriented in the problem, which is probably also due to his active work in the production company, which implies the possibility of practical deployment of the developed equipment directly on the chain conveyor used in the paint shop of the company. In the field, he has clearly demonstrated the corresponding knowledge he used to design his own solutions in DisP.

Formal level of work

DisP is processed in logical sequence and systematic way. However, in Chapter 8, information is presented in such a way that it is problematic to orientate in them and to find the correlation between results obtained by analytical calculations and FEM calculations. This has led to problems with the correct understanding and interpretation of the results presented. The DisP language level is at a good level and the graphic design has a level corresponding to the commonly presented DisP.

Dissertation queries

1. How related the resulting values given for each variant in Chapter 8 in the tables (analytical method of calculation) with the resulting values obtained by FEM, or what is the actual purpose of the FEM analysis performed? For example, FEM analysis results show that in variant I., in some cases, the yield strength of the material used was locally exceeded. However, the results presented in tab. 8.1 do not suggest anything like this.
2. In the DisP designed device was installed on the chain conveyor in the paint shop ŠKODA AUTO a. s., do you have any feedback about its operability and the ability to diagnose a possible low-speed bearing failure in time?

Closing statement

Based on the above, I recommend the dissertation work of **Michael Oeljeklaus** for the defence and in the case of a successful defence, I recommend to give the Ph.D. student an academic title

„Ph.D. "

doc. Ing. Václav Vaněk, Ph. D.

In Pilsen 12. 4. 2019