Development of a Cause-effect Relationship Model to Identify Influences on Load Conditions that Cause Bearing Damage

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When considering the influencing factors that may cause damage to occur within a bearing, it is important to note that one cannot trace the cause back precisely. These influencing factors may range from being temperature changes, external forces and lubrication choices. The load conditions in technical systems depend on many influences. This paper presents a model that supports the identification of the relevant influences on load conditions that cause bearing damage, to enable bearing durability tests. The development of the presented model is based on consideration of pitting as well as widening of the bearing raceway and edge throw-ups. The influences that the before mentioned considerations have on the load conditions as well on the occurrence of the damage were unknown. Furthermore, findings from damage catalogs and theoretical system analysis were used in combination with experimental investigations. The developed model links the following external influences to have an effect on bearing damage: load conditions, operation-dependent parameters in the bearing, physical and chemical mechanisms as well as appearance of the damage. The presented model can be used to identify the following: influences that lead to main loads, parameters that reinforce damage mechanisms, cycles that are self-reinforcing, and parameters that contribute to multiple damage mechanisms. The before mentioned facilitates the formulation of relevant influences on load conditions for bearing durability tests.

Keywords: durability test, bearing, load conditions, cause-effect relationships, test rig, system analysis.

1. Introduction

Using test rigs to investigate technical systems and their subsystems, the influences of individual parameters and their interactions on reliability can be investigated. This is usually done through carrying out reproducible experiments. Subsystems and component tests can be more effective and result in less expensive test effort (O'Connor 2001). Only if the influences and interactions are known, a system can be further developed in a focused manner. For a product developer to be able to specify the durability of bearings in technical systems, load conditions and load collectives must be known. Influences on the load conditions and interactions of subsystems in the overall system are often unclear. However, they are required for durability tests on component test rigs. A challenge in determining the influences on load conditions is that in the area of reliability, many influences interact and hence can intensify.

In this paper, a bearing that converts a rotational motion into a translational motion while simultaneously applying a force eccentrically towards the outer ring is used as an application example. This bearing was chosen such that an identification of relevant influences and load conditions on itself can be found, during a bearing durability test. Through using a theoretical and experimental analysis on a developed test rig, the relationships between influences on load conditions and failure modes is built.

Starting from research into the identification of influences on load conditions, the state of the art of modelling influences on load conditions in known bearing durability test rigs is introduced in the following subchapters.

1.1. *Identification of influences on load conditions*

To analyze and identify influences on load conditions that cause component damage, the procedure in VDI 3822:2011-11 can be used. There, a general procedure for carrying out a failure analysis is presented. The procedure starts with the description of the failure and the record of failure history.

While failure hypothesis are derived and instrumental analyses are performed, the investigation results lead to the cause of failure. The procedure provides guidance on what steps should be taken in a damage analysis, but it does not specifically address bearing damage analysis to identify influences on load conditions. In (Lange and Pohl 2014), another procedure for analyzing damage cases is presented. Another source that can support the identification of influences on load conditions are damage catalogs from bearing manufacturers (Schaeffler Technologies AG & Co. KG 2000; SKF Groupe 2008). They list damage patterns and provide information on possible influences that could have led to a failure mode. However, they only represent individual correlations and can therefore not be used directly to identify the influences on load conditions and their interactions. In (Czichos and Habig 2020), damage mechanisms are described and assigned to damage patterns. It is important to note that interactions between damage causes are not shown.

While influences such as temperature, external forces and the lubricant are able to interact with each other, their characteristics are usually not known in the system. Therefore, while failure analysis is supported, it is not clear which influences on the load conditions of the bearing are relevant for the damage, how these influences interact with each other and how they have to be taken into account in a durability test.

1.2. *Modelling of influences on load conditions in known bearing durability test rigs*

Laski et al. (2019) presents the design of a test rig for rolling bearing durability testing. The test rig includes a longitudinal and radial load unit as well as a drive and a temperature control unit for the lubricating oil. Laski et al. found out that one of the greatest influence factors on the durability is the power load. Furthermore, Jacobs et al. (2012) describes a test rig for rolling element bearings. The test rig includes a multi-axial load unit with separately controlled static and dynamic forces in radial and axial direction. For the main spindle drive adjusted bearings were used due to system stiffness and lifetime requirements of the spindle bearings. Chmelar et al. (2020) presents a bearing test rig which can apply a static radial load and dynamic axial forces simultaneously. The lubrication state can be adjusted and is monitored via a lubrication state sensor and temperature sensors.

In current published research, there are examples of test rigs with which durability tests can be performed. These take into account the axial and radial forces as well as the lubrication condition and temperature conditions of the bearing under test. The aim of this study is to identify the relevant influences on load conditions for reliability testing and develop a cause-effect model. Therefore, an investigative case study is conducted. We investigate the interactions between external influences on the bearing and thus the influences on the load conditions, operation-dependent parameters in the bearing, physical and chemical mechanisms and the appearance of the damage.

2. Materials and Methods

2.1. *Case of the investigative study*

In an axially and radially loaded bearing, pitting, tread pattern widening and burr on tread edge occur as shown in Figure 1. The damage ultimately leads to the failure of the system. Tests to isolate the causes of damage are very time-consuming and cost-intensive in the system under investigation. The loads and the boundary conditions that cause these loads are complex and not directly apparent in the bearing investigated, and thus not easy to reproduce. For this reason, a durability test rig for bearings is to be developed which enables easily reproducible tests. This would make it possible to vary individual influences on the load conditions of the bearing, effectively allowing to test the durability without the residual system. Moreover, it would then be possible to further develop the bearing.

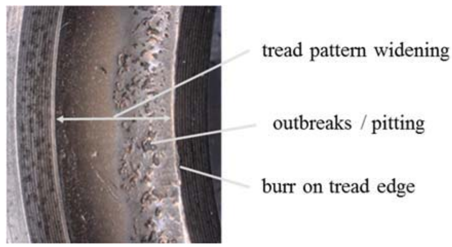

Fig. 1. Damage pattern of the case of the investigative study

Figure 2 shows the mounting situation of the bearing under investigation. The bearing converts the shaft's rotational motion into a translational motion in order to move an adjacent component. The oscillating translational motion of the adjacent component results in an oscillating force directed eccentrically towards the outer ring. The case is used as an application example for complex loads on bearings.

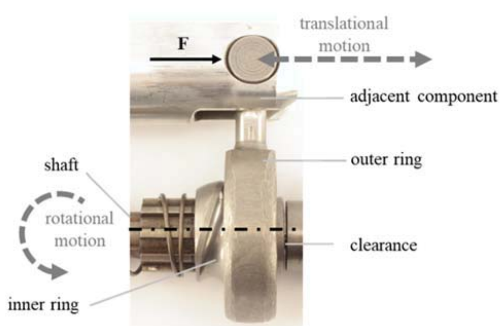

Fig. 2. Assembly situation of the investigated bearing

2.2. *Procedure for the identification of the influences on load conditions*

In order to identify the relevant influences on the load conditions that occurred, findings from a damage catalog (Schaeffler Technologies AG & Co. KG 2000) were combined with a theoretical and experimental analysis before finally being integrated into a model. The findings from the damage catalog gave indications which influences should be investigated in more detail. The findings; however, were not sufficient to identify the relationship between influences on load conditions and failure modes as well as their interactions, which is needed for a bearing durability test rig. Based on VDI 3822:2011-11, a theoretical analysis of the system and damaged bearings was performed (Figure 3). For the individual steps of the procedure proposed in VDI 3822:2011-11, it is necessary to identify influences on the load conditions and interactions and to evaluate their relevance for damage occurrence. This was done by using methods that are listed in Figure 3, on the right.

Furthermore, the following will be presented in chapter 3.1: the results of the analysis of the force progression and the force distribution, the simulative analysis of the dynamical system behaviour and the analysis of the lubrication.

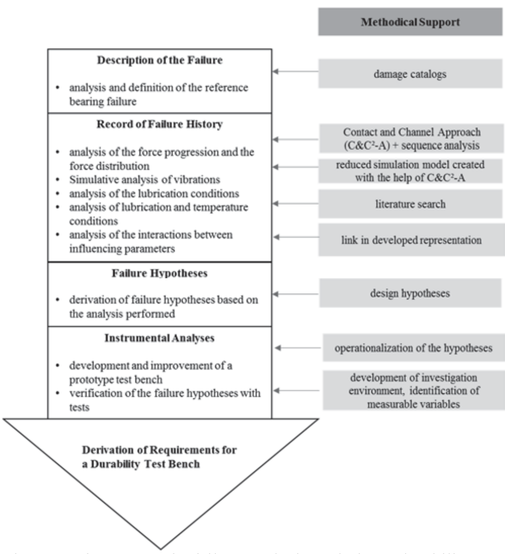

Fig. 3. Performance of a failure analysis to derive a durability test based on VDI 3822:2011-11 and the used methodical support in the individual steps.

With the aid of a developed test rig, individual influences on load conditions could be investigated experimentally and thus were verified. The design of the test rig is shown in Figure 4. The test rig was iteratively supplemented with possible influences on load conditions in order to further narrow down the influences on load conditions that cause damage. Adjustable influences were the axial clearance, the forces acting on the bearing and the lubricant. The temperature on the bearing outer ring was measured as a control variable. Additionally, the axial clearance can be adjusted. Both the amplitudes of the applied force characteristic and the force characteristic itself can be varied. The speed can also be varied, and speed curves can be set. To investigate the influence of lubrication, various states of the lubricating medium were simulated.

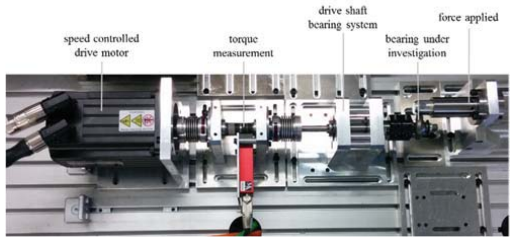

Fig. 4. Bearing test rig used for the experimental analysis of influences on load conditions.

2.3. *Structure of the model of relationships between failure modes and influences on load conditions*

Durability tests are often time-consuming and cost-intensive. It is important to prepare the knowledge required for these tests and generated in the process and to document it for comparable cases. Therefore, a model of relationships between failure modes and influences on load conditions is to be used to support the consideration of necessary tests used to identify influences on load conditions. The structure of the model is presented below. The model depicts the relationship between the failure modes of the damage, the physical and chemical mechanisms and parameters that occur in the bearing as a result of operation, and influences that act on the bearing from outside the bearing. It visualizes the relationships between the mechanisms and influencing parameters by means of directed connections. It is intended to support the delimitation of relevant influences on load conditions. The model depicts gain factors, influences that contribute to a mechanism (+), and causes where either one or the other influence must occur to provoke a damage (or).

3. Results

The following subchapters present the theoretical system analysis and the developed model of relationships between failure modes and influences on load conditions.

3.1. *Influences on the load conditions derived from the theoretical system analysis*

Based on the performance of a failure analysis in VDI 3822:2011-11, as described in chapter 2, a system analysis was performed to identify influences on load conditions that might have caused the damage and, hence, should be reproduced on a test rig to investigate durability. In the following, parts of the step ‘Record of Failure History’ and thus the analysis of individual aspects are discussed.

3.1.1. *Theoretical analysis of the influence of force progression and the force distribution*

Using the C&C² approach and a sequence analysis (Matthiesen 2021), the load on the bearing was divided into individual states which are analysed. The C&C² approach makes it possible to qualitatively identify the locations of the load in the individual states based on the analysis of the force flow. To visualize the theoretical load on the bearing's raceway, the raceway was unrolled, as shown in Figure 5. Based on the theory of damage accumulation, the theoretical load was accumulated (Siemon 2008). In the top part of the figure, the theoretical load on the running surface is shown, summed up over the various states. To verify the analysis and the hypothesis that the forces acting on the bearing contribute to the damage, the damage pattern of a bearing damaged in the original system was also visualized on the unrolled running surface. The result shows that damage occurs at points where a high load is assumed. The theoretical observation and the damage pattern are in accordance with each other.

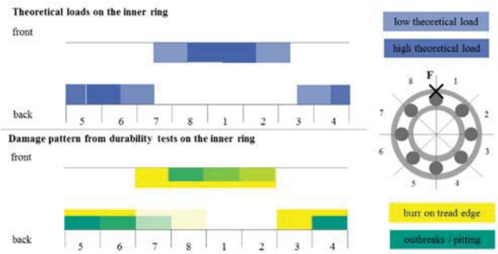

Fig. 5. Analysis of the damage pattern and the theoretical load.

3.1.2. *Simulative analysis of the influence of clearance on load conditions*

Analysis of the damaged system revealed clearance between components at several locations. In order to better assess the effects of this clearance, a multibody simulation was used. For this purpose, the bearing and the surrounding components were implemented in a Matlab Simscape model. The structure of the multibody simulation is presented in Figure 6. The path dependent force curve F(x) and the rotational shaft speed φ(t) were used as input variables. The output variables were the bearing position y(t) and the position of the adjacent component x(t). The clearance in the bearings was modelled by a path dependent stiffness and damping coefficient. This clearance was varied between 0.02 mm and 0.2 mm. It has been shown that clearance in the bearing can significantly influence the possible load F(t), as clearance has an influence on the bearing position y(t) and adjacent component position x(t). The speed-induced oscillations in particular can lead to larger load amplitudes F(t) with a bigger clearance, as they both influence each other.

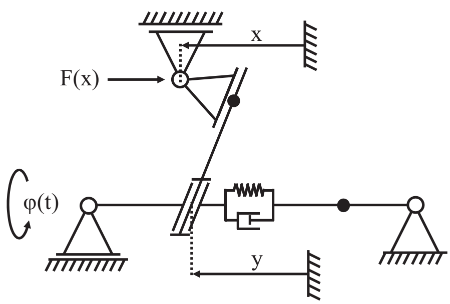

Fig. 6. Structure of the multibody simulation

3.1.3. *Analysis of the influence of lubrication and temperature on load conditions*

Due to its application, the bearing is not sealed. In order to assess the condition of the lubrication and the resulting loads on the bearing, the temperature of the bearing was measured and compared with the operating temperatures of the lubricant. The temperatures that occur are at the limit of the operating temperature. In addition, the composition of the contaminated lubricant was analysed, since the contaminants could cause additional force peaks when they roll over.

3.1.4. *Experimental analysis of influences on the load conditions in a durability test rig*

Theoretical analysis was supplemented by experimental studies to verify the influence of individual parameters. For this, we used the test rig described in Chapter 2. In order to identify the relevant influences on load conditions individually, the developed test rig was iteratively supplemented with possible influences on load conditions. In summary, it can be said that high axial forces from the outside onto the bearing, axial clearance in the bearing and contamination and pre-treatment of the lubricant could initiate damage within the bearing. The model, presented in Chapter 3.2, could be used in the selection of suitable experiments and the interpretation of the experimental results. For example, high mechanical loads were suspected to contribute to the three failure modes of: pitting on the track, burr on tread edge and tread pattern widening. It was also concluded that abrasive wear can lead to an increase in mechanical load and contamination of the lubrication. Hence, this would lead to a significant influence on the development of the failure modes. In the process of the tests carried out, a reduction of 33% in the force acting on the bearing was observed which can be attributed to a widening of the raceway.

3.2. Model of the relationships between failure modes and influences on load conditions

Figure 7 shows the developed model of the relationships between failure modes and influences on load conditions. The left column shows failure modes of the damage that occurred in our case. In the second column from the left, physical and chemical mechanisms are assigned to these failure modes. The two columns on the right represent operationally dependent parameters that occur in the bearing and influences that act on the bearing from outside. Cause-effect relationships are represented by directional arrows connecting two parameters. In addition to operation-dependent parameters that trigger damage mechanisms, connections were also established between damage mechanisms and the operation-dependent parameters. An example is the damage mechanism abrasive wear. The particles generated by this mechanism contribute to greater contamination of the lubricating medium. It is important to note that there are relationships in which two operation-dependent parameters or influences that act on the bearing from the outside must first occur in order to trigger a damage mechanism. Therefore meaning that one parameter alone does not trigger a damage. An example of the before mentioned is the formation of pitting due to Hertzian contact. This mechanism is associated with mechanical load in the rolling contact and relative motion between the rolling element and the raceway. Another noticeable aspect is that there are parameters that contribute to several damage mechanisms. For example, the mechanical load in the contact between the rolling element and the raceway, combined with other parameters, can lead to both plastic deformation at the raceway edges and Hertzian compression underneath the raceway.

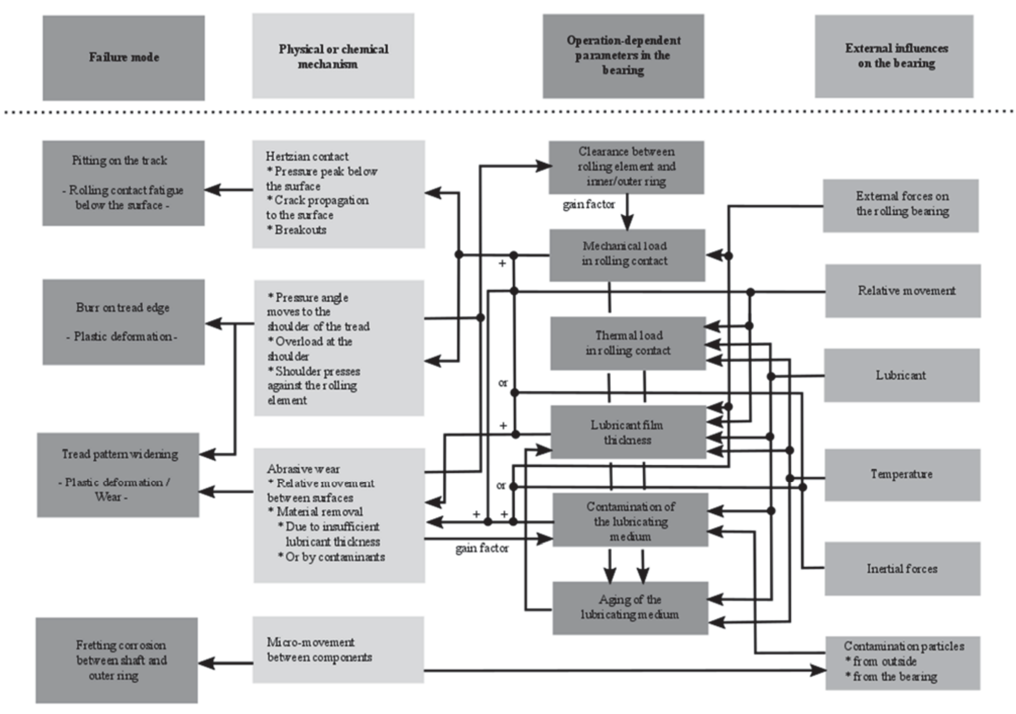

Fig. 7. Developed cause-effect model of the relationships between failure modes and influences on load conditions of bearings.

The operationally dependent parameters that occur in the bearing during operation are affected by influences such as external forces and temperatures. In the figure, parameters are shown with ‘or’ links. Here, it is sufficient for one of the two influences to occur to initiate the respective damage mechanism. However, the two influences can also both occur simultaneously. Operation dependent parameters and influences, which are connected with a ‘+’ in the model, must be present at the same time in order to trigger a mechanism.

4. Discussion

The cause-effect model of the relationships between failure modes and influences on load conditions clearly shows which combinations of parameters have an effect on a specific damage mechanism. Furthermore, operation dependent parameters and external influences on the bearing that only cause failure when they occur in a combination exists as well. This is the case for load and lubricant film. These parameters and influences are particularly difficult to take into account in the load profile because the combination of factors must be set suitably. In contrast to the damage catalogs by Schaeffler Technologies AG & Co. KG (2000), the presented model showcases how some influences on load condition contribute to several failure mechanisms. Additionally, the model describes self-amplifying or damping effects. In the case of self-amplifying effects, a closed loop between mechanisms and operation-dependent parameter can lead to highly progressive wear, as in Figure 7 between the mechanism 'overload at the shoulder' and the operation-dependent parameters 'clearance between rings and ball' and 'mechanical load in rolling contact'. As external influences can contribute to additional energy created in the system, the model considers the influences and their interaction to other damage mechanism in order to assess the resulting failures.

The cause-effect model can be used to derive hypotheses which can be tested on the test rig. As the focus was to identify parameters that have an effect on load conditions resulting in bearing damage, relevant interactions must be determined. A high number of tests would be required in order to determine these interactions by testing the bearing in the overall system with design of experiment (DOE). According to design of experiments, using a fractional factorial design would reduce the effort. However, the use of fractional factorial design is still time-consuming when considering a large number of parameters and higher-level interactions due to the lack of knowledge regarding their impact. With the hypotheses that were derived from the cause-effect model, the test design can be reduced to the relevant parameters. By reducing the parameters and their interaction with the cause-effect model, much time can now be saved when using a fractional factorial design for testing. In the presented model, compared to an analysis of the system using an FMEA or FTA, interactions and factors that amplify a mechanism can be taken into account.

The iterative procedure for the integration of the influences on the load conditions enabled a targeted adjustment of the failure mode. Such fine tuning is advisable when component tests with substituted loads are to be investigated on a test rig. Limitations of the results are to be found in the small data basis of the cause-effect model, which is based on the case study described. In order to extend the cause-effect model, further influencing factors should be taken into account for different test situations.

5. Conclusion

In this paper, a model for identifying influences on load conditions that cause bearing damage was developed. The model depicts the relationships between external influences on the bearing and thus the influences on the load conditions, operation-dependent parameters in the bearing, and physical as well as chemical mechanisms and the failure modes. The model was developed in a case study in which pitting as well as widening of the bearing raceway and edge throw-ups occurred at a bearing. Theoretical analyses and experimental analyses were performed on a test rig and combined with findings from damage catalogs. With the help of the developed model, the following relationships could be identified:

- There are cycles that can be self-enforcing.
- Some factors lead to a failure only when appearing in combination.
- The damage mechanisms can lead to a change in the operation-dependent parameters.

The cause-effect model can be used to design durability tests.

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