Investigations on the rolling bearing cage dynamics with regard to different operating conditions and cage properties

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Abstract. The dynamic behavior of a cage can have a significant influence on the performance and the noise of a rolling bearing. In case of an unstable or high-frequency cage movement, vibrations are transmitted to the adjacent machine elements and the environment, which can influence the operating behavior of the whole system. In addition, a loud noise can often be perceived, which is referred to in the literature as cage rattling or squealing. In this paper, characteristics of different cage movements are investigated using multibody simulations and experimental investigations. For this purpose, essential properties of the fundamentally observable cage movement types “stable”, “unstable” and “circling” are presented. The calculated cage dynamics and the type of cage motion are used to show dependencies between the operating conditions and the resulting cage movement such as inner ring rotational speed, bearing load or cage characteristics such as pocket clearance. Based on the simulations, interactions between the input parameters can also be determined. The results are used to identify operation-critical conditions and cage properties that lead to high cage dynamics. Finally, a comparison between the results of the multibody calculations and optical measurements is made. The optical measurements are performed using high-speed cameras. Reference markers fixed on the cage and digital image correlation allow the evaluation of the kinematics as well as the deformation of the cage. These results are compared with the simulation data to ensure a high quality of dynamics simulation.

Dependency of unstable cage motion on the coefficient of friction in contact between cage/rolling element and speed of the inner ring. An interpolation between the simulation results shown as black dots is color highlighted.
1. Introduction
The demands on the performance of rolling bearings are continuously increasing. In addition to conventional functionalities such as shaft guidance or load rating, the focus is also on vibration and noise behavior. A possible cause of severe vibrations or noise can be the cage of the rolling bearing. Under certain conditions, the cage can perform very high-frequency movements, which can also be superimposed by severe deformations. In the literature this phenomenon is called cage rattling or cage instability [4; 9; 3]. In this case, the cage shows a high-dynamic movement which leads to an increase in contact forces, slip velocities and the frictional torque of the bearing. The severe deformations can also lead to high component stress on the cage and may significantly reduce cage lifetime. In addition high contact forces between the cage and rolling elements can affect the kinematics of the rolling elements and thus also lubricant film formation and bearing lifetime. In addition to this type of movement, which is classified as ‘unstable’, ‘stable’ and ‘circling’ movement patterns can also be observed [10]. During a circulating cage motion, the cage center of mass (cCoM) uses a major part given by the guidance clearance and the speed of the cCoM corresponds approximately to the rotational speed of the cage. A stable cage movement characterizes a very low dynamic. The cCoM of the cage moves comparatively slowly and the deformations of the cage are very low.

Research activities on cage dynamics are performed in the field of calculation as well as in real experiments. GUPTA used a dynamics simulation model to investigate the relationship between friction in the cage pocket and the resulting trajectory of the cage [5]. NOGI et al. determine a critical limit for the friction coefficient above which cage instability occurs. This limit was determined on the basis of dynamics simulations and depends on the cage mass, the friction in the contact between ball and raceway, cage-ball contact stiffness, speed of the cage and number of rolling elements [8]. There are also publications in the experimental area dealing with the dynamics of rolling bearing cages. The cage movement is often measured using optical methods (high-speed cameras). These are suitable for contactless determination of the cage movement even at high rotational speeds. ABELE and HOLLAND were able to observe a clear influence of accelerations of the rolling bearing and the resulting cage motion on the basis of measurement results [1]. ABELE, UNTERDERWEIDE and HOLLAND were also able to measure typical properties of unstable cage motion in experiments [2]. SCHWARZ, GRILLENBERGER and TREMMEL used high-speed cameras and digital image correlation to compare the deformations of unstable cage motions in calculation and experiment [9].

The previous investigations only selectively show the influence of the bearing load or cage geometry on the resulting dynamics. A comprehensive study is not available in this context. In the following, based on a comprehensive simulation study dependencies between parameters such as bearing load, rotational speed as well as cage pocket clearance and the resulting cage movement identified for a deep groove ball bearing. Thus, interactions of the investigated parameters with respect to the resulting cage dynamics can be determined, further improving the understanding of highly dynamic cage motions.

2. Main Section
2.1. Test and simulation conditions
A deep groove ball bearing with an inner diameter of 65 mm, an outer diameter of 140 mm and a glass fiber reinforced polyamide cage is used for these investigations. The multi-body simulation software Caba3D (Computer Aided Bearing Analysis 3 Dimensional) is used to calculate the dynamics of the rolling bearing and in particular of the cage. Caba3D enables the determination of all kinematic and kinetic results of the rolling bearing components [7; 9]. In addition, a reduced finite element model is used to calculate the elastic deformation of the cage [7; 4]. The deformation is an elementary characteristic of the unstable cage motion and should therefore be taken into account in the simulation.

An important parameter regarding the cage dynamics is the friction force between cage and the rolling elements [5, 8]. This is considered in Caba3D according to COULOMB’s friction model and consequently with a coefficient of friction $\mu$. This method allows the simplified modelling of different lubrication conditions, e.g. dry or lubricated and is considered reasonably accurate, since it is not the friction force
itself but its effect on the cage dynamics that should be calculated within the scope of the simulation. In particular, for the unlubricated contact between the cage and the rolling element, COULOMB's friction model is considered adequate. Although the coefficient of friction shows tendencies for different lubrication conditions, there is no specific value for a given lubrication. Therefore, for the comparison between the simulation and the optical measurement, several simulations with different coefficients of friction are carried out.

A stereo camera system enables the measurement of the cage kinematics. The image section is captured at 8 000 fps. Reference markers are attached to the test rig, shaft and cage. By grouping these markers to form a component, all translation and rotation movements of these components can be determined using digital image correlation. In addition, the cage deformation is calculated by shifting the original pattern to the deformed pattern. Deformations can thus be determined on the basis of the deviations from the original pattern.

The Cage Dynamics Indicator (CDI) is calculated to assess the cage dynamics. This indicator forms the basis for quadratic discriminant analysis, which determines the class probability for the given cage movement [10].

2.2. Influences on cage dynamics

Latin Hypercube samplings were performed to determine the influence of friction coefficient (in the cage pocket), bearing load, inner ring rotational speed and pocket clearance on cage dynamics. The limits for the experimental design of the calculations are especially for the friction coefficient $\mu = 0.5$ high, in order to better analyze the influence of the parameters. In addition, increased coefficients of friction are to be expected especially in the contact of polyamide and steel without lubricant, which are in the range specified [6]. For each of the simulations, the motion type was determined using quadratic discriminant analysis and the CDI. Figure 1 illustrates the relationship between the probability of “unstable” class membership $P_I$ as a function of friction coefficient, radial bearing load, load ratio (axial force divided by radial force) and pocket clearance based on an interpolated surface.

The coefficient of friction in the cage pocket has the greatest influence on cage movement, which is why the other influencing factors are shown in combination. From a friction coefficient of 0.4, only unstable cage movements can be observed. Above a certain amount of frictional force, unstable cage movement is therefore to be expected independent of the operating condition. In contrast, no tendencies towards unstable cage movement can be observed at coefficients of friction of less than 0.1. This means that unstable cage movements can be avoided as good as possible by reliable lubrication of the contact between the cage and the rolling element, which ensures a coefficient of friction of less than 0.1. The rotational speed of the inner ring also influences the cage dynamics. Accordingly, figure 1 shows that an increase in speed can lead to unstable cage movements. From about 5 000 rpm, there is no change in the probability of unstable cage motion. With respect to the load, it should be noted that higher radial
loads and load ratios of less than one tend to prevent unstable cage movements, since in these areas only higher friction coefficients lead to cage instability. From a load ratio of more than two, hardly any change in the influence on the cage dynamics can be detected. Finally, the cage pocket clearance also shows an influence on the cage dynamics. Small values of the pocket clearance increase the tendency to unstable cage movement. In addition, it is also possible to identify pocket clearances that are particularly suitable for reducing the probability of unstable cage movement.

2.3. Comparison with optical measurements

With the help of optical measurements, the quality of the simulations can be assessed and a range for the coefficient of friction can be identified which offers a good match with the simulation. Figure 2 shows the cage cCoM trajectories for the measurement and three simulations with different coefficients of friction. The simulation with the smallest coefficient of friction of 0.01 shows a circumferential cage movement, while the simulations with higher coefficients of friction of 0.3 and 0.5 show unstable cage dynamic. In addition, it is obvious that an increase in the coefficient of friction leads to unstable cage movement under otherwise constant operating conditions.

![Figure 2. Trajectory of the cage cCoM for the optical measurement, and three simulations with different coefficients of friction. The speed of the inner ring is 1 500 rpm, the load on the bearing is 3 000 N in the axial and 1 500 N in the radial direction. No lubricant was used in the experiment.](image)

In addition to the cage cCoM motion, the deformation of the cage can also be used for the comparison, see figure 3. As expected, comparatively high deformation values can be observed in the unstable cage movements, which lead besides loud noise to high and fast changing loads and a negative impact on the lifetime of the cage. In the optical measurement the highest amplitudes are present at a frequency of 477 Hz and 550 Hz. In comparison, the frequencies of the unstable cage movements in the simulation are somewhat higher. Thus, high amplitudes are present at a coefficient of friction both in the range of 453 Hz and 738 Hz. The differences are due to the glass fibre reinforced material of the cage, whose anisotropic material behavior is not considered in the simulation. Nevertheless, both the measured and the calculated cage dynamics at the coefficients of friction of 0.3 and 0.5 can be clearly classified as unstable. In principle, a high correlation between simulation and measurement can be determined. For a detailed evaluation of the agreement between calculation and measurement in the context of a validation, further measurements will be considered.
Figure 3 Deformation of the cage for optical measurement and three simulations with different coefficients of friction. The speed of the inner ring is 1 500 rpm, the load of the bearing is 3 000 N in axial direction and 1 500 N in radial direction. No lubricant was used in the experiment.

3.4 Summary and conclusions
Based on a large number of simulations, dependencies between an unstable cage motion and the friction coefficient in the cage pocket, bearing load, bearing speed and cage pocket clearance are determined. Thus, it can be observed that for the investigated cage high coefficients of friction, high bearing speeds, load ratios greater than 2 and small pocket clearance support unstable cage motion. Finally, a comparison between optical measurements and dynamics simulations shows that the simulation results correlate very well with the measurement and thus with the actual cage movement. An unstable cage movement can be observed during the optical measurement, which can also be observed in the simulation. For the calculation, a coefficient of friction of 0.3 or higher must be defined, which can be considered plausible for the material pairing of polyamide and steel [6] in a contact without lubrication.

Based on these relationships, the operating conditions for the cage that lead to unstable cage motion can be identified for the analyzed rolling bearing. For example, by improving the lubrication condition in the contact between the cage and the rolling element, it is possible to reduce the friction and thus the dynamic behavior of the cage. Particularly at high speeds, sufficient lubrication should be ensured, as cage instability is stimulated under such conditions. Also, in the case of axial preload, this could be modified to vary the load ratio in order to avoid unstable cage movements. Adapting the cage geometry to influence the guidance and pocket clearance would be a suitable approach for affecting the resulting cage dynamics. In this way, the dynamic properties of the rolling bearing cages can already be taken into account by the simulation during the design process.

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