Application of an Optomechanical Image Derotator for Measuring Vibration and Deformation of Rotating Objects

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Abstract

Most rotating machinery parts like roller bearings or jet engine components are subject to high static and dynamic loads during operation. These excitations cause in-plane and out-of-plane deformation and vibration of the machinery parts, which can lead to minor operation performance, higher wear rates and finally the destruction of these components. Hence, it is of interest to acquire appropriate information about the dynamic behaviour of the machinery parts during service. This paper presents an approach of optical vibration and deviation measurement for such components. Essential for this method is an optomechanical image derotator combined with a high speed camera or a Laser Doppler Vibrometer (LDV). This paper first summarizes the principal of the image derotator and the experimental setup for the in-plane and out-of-plane measurements. By the combination of the derotator and the high speed camera, a derotating image of the moving component is generated and thereby the in-plane deviation can be determined. Exemplary for the in-plane measurement method, experimental results of roller slippage of a cylindrical roller bearing under operation conditions is presented. In the case of LDV and the image derotator, the laser beam is guided onto a rotating component and performs a uniform rotational motion. Thereby, it is possible to measure the out-of-plane vibration of the rotating object in a coordinate system that rotates with said object. Following this approach, the results of the vibration measurements of a rotating saw blade by scanning LDV and image derotator will be presented.

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Introduction

Most rotating machinery parts do not only rotate, they are often subjected to additional excitations. These excitations can lead to minor performance and more wear and finally to the destruction of these components. Hence, it is of interest to have appropriate information about deformations and deviations caused by external excitations. Examples for these effects are processes with cut off wheels, grinding wheels, turbine blades under heavy loads of air or fluid as well as brake discs or bearings under operational conditions. In all these applications, analyses of the dynamic behaviour of rotary machine parts are desirable.
Out-of-plane vibrations can be determined by using optical methods like double exposure Holography or Laser-Doppler-Vibrometry (LDV) [1, 2]. The in-plane deflections are commonly measured using image processing techniques or Speckle correlation [3, 4]. These techniques work well for static object and can also be applied to rotating objects. However, to compensate for the rotation of the object, it is necessary to track a measurement point on the object either with image processing techniques or with a laser beam. Therefore, the sample rate of the camera or the maximal tracking speed of the LDV laser beam limit the maximal rotation frequency of the object at which measurements can be carried out. To overcome this drawback, the method that is used in this paper is based on an optomechnical image Derotator and image processing methods as well as Laser-Doppler-Vibrometry.

Working Principle of the Derotator

The main component of the derotator is a dove prism. As the prism is rotated, the image passing through will rotate at twice the angular rate of the prism (Figure 1). The dove prism is used to eliminate the object rotational movement from the image. To receive an optimal derotated image, the optical axis of the prism, the rotary axis of its drive and the rotary axis of the object must be identical and also the prism must rotate with half of the rotational frequency of the rotating object. The dove prism is located at the centre of a hollow-shafted torque motor. The speed of the motor is controlled by a cascade control implemented in Matlab xPC Target such that the rotational speed of the derotator and the object amounts a ratio of 2:1. Figure 1 shows the optical principle of the derotator.

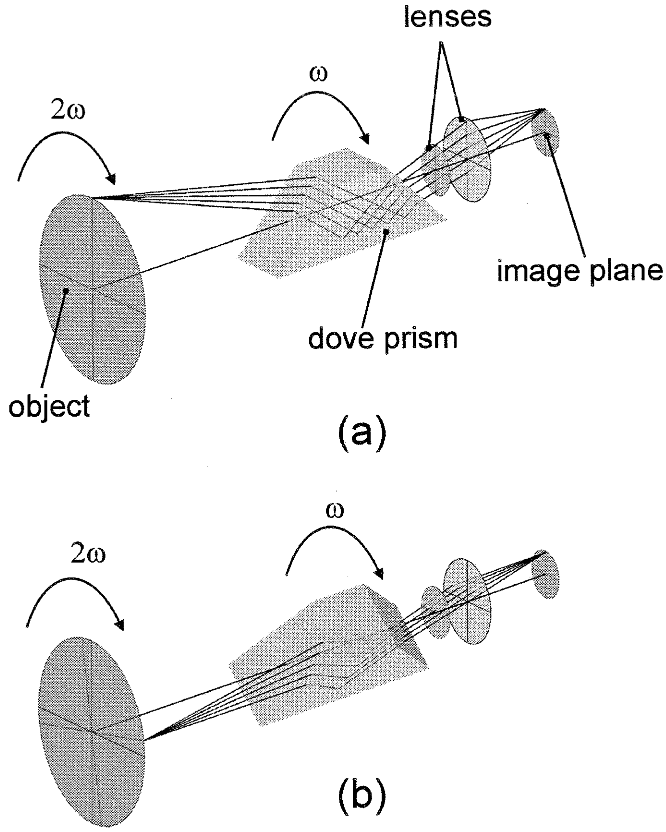

Figure 1: *Optical path through the dove prism for two different rotation angles (a) object rotation angle 2ω = 0° (b) object rotation angle 2ω = 80°[5]*

Application Examples

In-Plane Measurements

As an example for in-plane measurement, the dynamic slippage behaviour of roller elements during bearing operation will be introduced. Slippage happens due to a difference between the theoretical rotational frequency of the roller elements and their actual rotational frequency. Unsteady skidding motions cause damage at the bearing surface. Due to the relative motion, solid body friction occurs. Thereby, during the relative motion of the rolling element on the raceway surface, a sufficient lubricant film can not be generated. The surfaces are not completely separated. As a result, surface damage in terms of smearing occurs. During further operation of the bearing, fatigue and cracks develop at the raceways. Resulting damage affects the operational behaviour and noise emission of the roller bearing significantly. Also, the bearing lifetime can be reduced [7]. Up to now, a limited range of slippage measuring methods for bearings exist [7]. Unfortunately, these methods are complex to apply and only suitable for a small number of bearing types, especially for big-sized bearings (30-60 mm roller diameter) [7]. The majority of bearings in industrial applications have smaller dimensions. Thereby, these bearings are difficult to examine with the present methods. For measuring the roller slippage, it is necessary to measure the real rotational frequency of the roller. The setup, which is used to determine the real rotational frequency within this paper, is shown in figure 2. It consists of a bearing setup, an image derotator and a high speed camera. The high speed camera is a CMOS-Camera with a recording frequency of f = 500 images/s at a maximum resolution of 1280 x 1024 pixels.

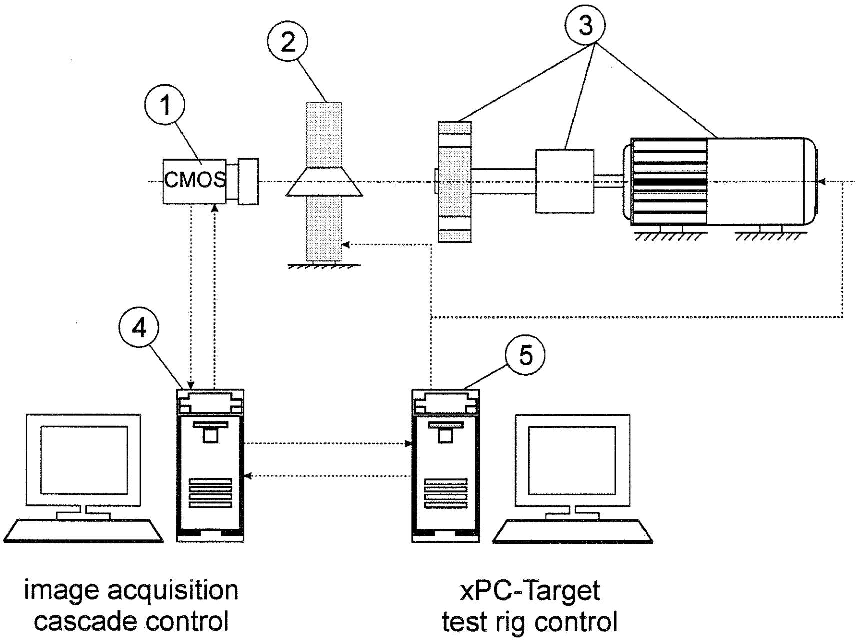

Figure 2: *Schematic view of the test rig. 1) high speed camera, 2) image derotator, 3) bearing set up 4) image acquisition and host PC for control calculation 5) XPC-Target for control implementation*

In this experimental setup, the dove prism rotates with half of the rotational frequency of the bearing cage f_c. Thus, it is possible to receive a stationary view of the cage and to observe the rotational movement of the roller elements around its own axes. For measuring the rotational frequency of the cage, a bar code is placed on the cage and its rotational frequency and direction will be measured with 2 photo electic sensors (Figure 3).

One of the rollers is marked on its surface three times. By tracking the three markers on the roller surface and calculating the distance that each marker covers between two frames, the roller rotational frequency f_{re} is determined. For tracking these markers, digital image processing algorithms are used.

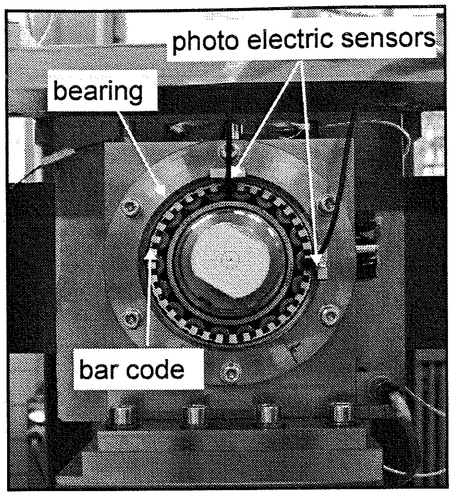

Figure 3: *Determine the cage rotational velocity*

During the measurements the shaft velocity and the applied load is varied. The results show, that this method is very applicable to measure the roller slip. Figure 4 shows exemplary the measured roller slippage S of the bearing during operation for different shaft rotational speeds n at a load $F_r = 16$ kN. The value $S = 0$ indicates no slippage. In this case, the roller rotates with the theoretical rotational speed. The value $S = 1$ indicates the complete sliding of a roller. In this case, the roller performs no rotation around its axis. The left part of figure 3 shows the roller slippage over its rotational angle around the bearing. In the right part of the figure the roller slippage is shown during one revolution of the bearing.

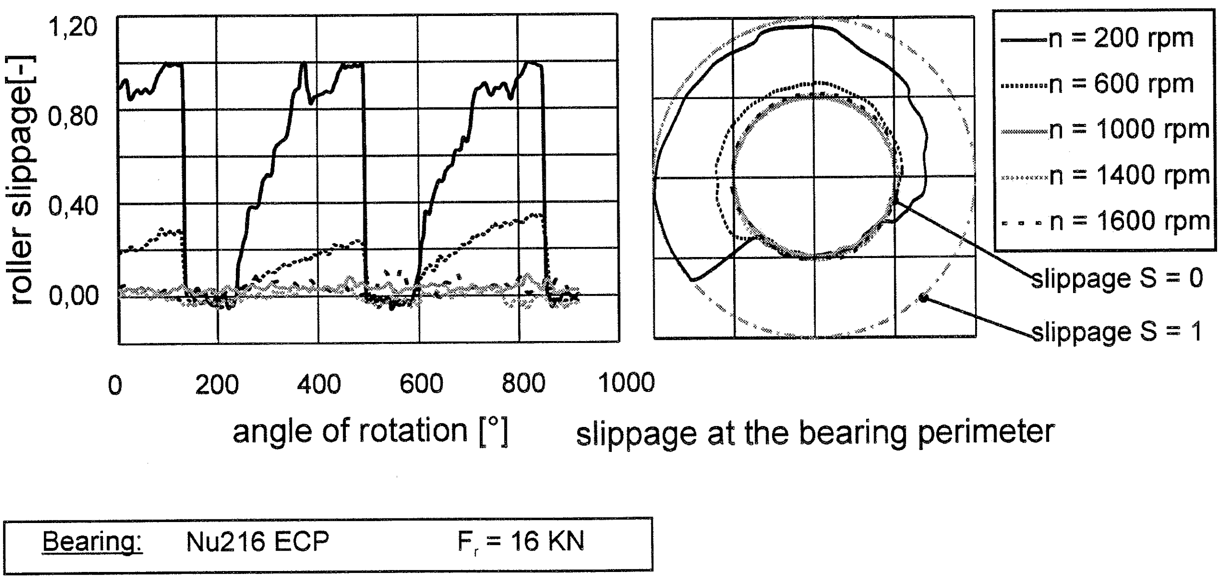

Figure 4: *Influence of the rotational speed on the roller slippage*

In this experimental setup the loaded zone of the bearing is located at the underneath of the bearing. As the roller arrives at the load zone of the bearing, no slip occurs. The roller rotates with its theoretical speed. As it leaves the load zone of the bearing, it slows down (delay zone) and the slip increases at a maximum. Afterwards it accelerates (acceleration zone) until it arrives again at the load zone. These 3 zones are principally shown in the Figure 5.

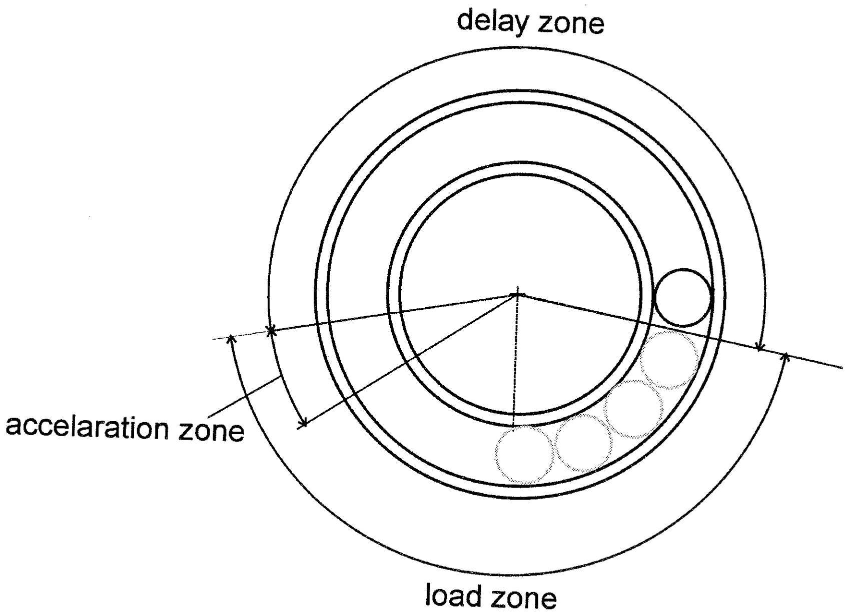

Figure 5: *Roller movement during bearing operation*

Additionally it is clearly to see, that with increasing shaft rotational speed a decrease of the roller slip occurs. One reason for this is the inertia of the roller.

Out-of-Plane Measurements

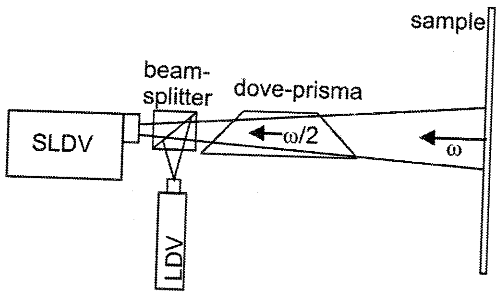

Figure 6: *Out of Plane Experimental Setup*

The experimental setup for the out-of-plane vibration measurements is shown in Figure 6. The measurement unit consists of two Laser-Doppler-Vibrometers (Polytec PSV400, Polytec PDV 100). A Scanning Laser Doppler Vibrometer (SLDV) is used to determine the vibration at discrete measurement spots on the rotating object. A second vibrometer (LDV) is applied as a

reference vibrometer in order to obtain the phase of the vibrations at different measurement spots during the scanning process. The laser beams of the vibrometers are directed through the Derotator (Dove prism) via a beam splitter.
In this paper we exemplarily present measurement data, which were obtained using a circular saw blade as a sample. The diameter of the blade was 1 m and the flange diameter 0,335 m. The measurements were conducted at rotation frequencies of the blade of ν_D = 0 Hz, 9.7 Hz, 13.1 Hz and 15.9 Hz. In order to determine the difference between measurements in a sample fixed and a lab fixed reference coordinated system, the eigenfrequencies and eigenmodes of vibration for each rotation frequency were measured with and without Derotator. The vibration of the blade was excited using a shaker.

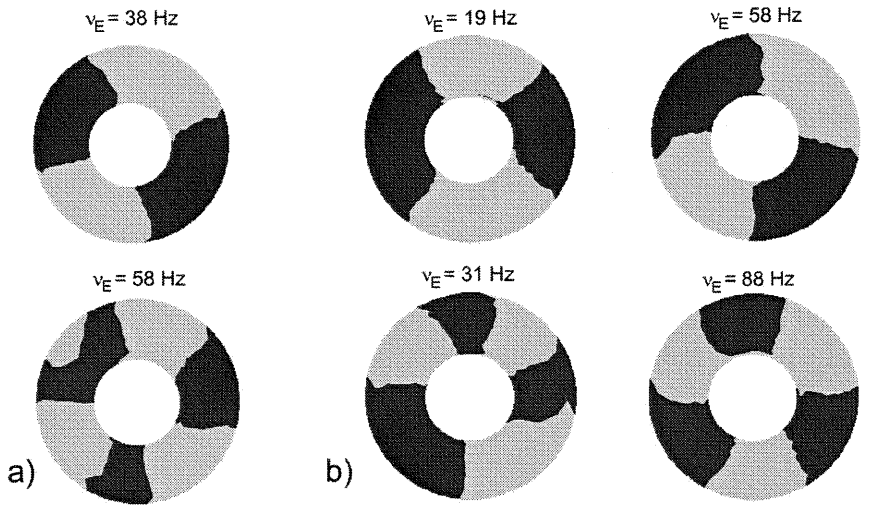

Figure 7: *eigenmodes and eigenfrequencies ν_E of vibration for a circular saw blade (rotation frequency (ν_D = 30 Hz): a) measured with Derotator, b) measured Derotator.*

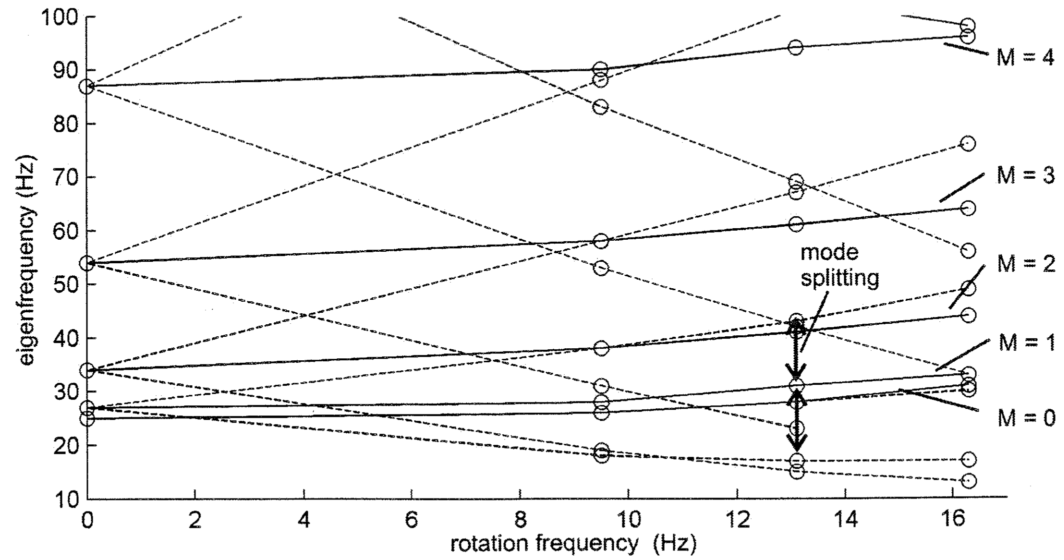

Figure 8: *Campbell diagram: eigenfrequencies measured with Derotator (solid lines) and without Derotator (dashed lines)*

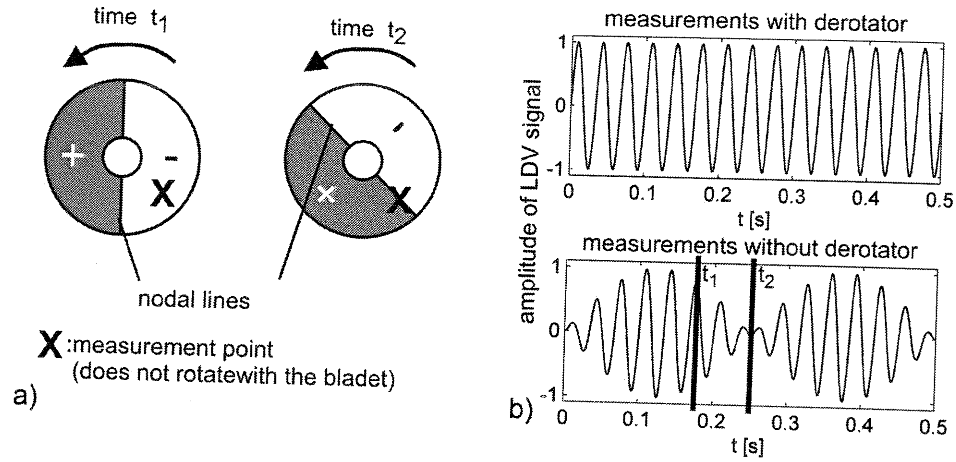

Figure 9: *a) sketch of a rotating blade at time t1 and t2; b) corresponding LDV-Signal measured at the measurement point X with and without Derotator[6]*

Some eigenmodes of the saw blade are exemplarily shown in Figure 7 for a rotation frequency of ν_D = 30 Hz. The corresponding Eigenfrequencies are denoted with ν_E. Figure 7a shows Eigenmodes, which are measured using the Derotator (reference coordinate system fixed to the sample), and Figure 7b shows Eigenmodes, which are measured without Derotator (reference coordinate system fixed to the lab). In comparison, the shapes of the Eigenmodes are identical in both cases. However, the corresponding Eigenfrequencies differ and in case of a lab fixed reference coordinate system there are two Eigenfrequencies showing the same shape of the modes of vibration.

The measured eigenfrequencies of the saw blade are shown in Figure 8 as a function of the rotation frequency (ν_D = 0 Hz, 30 Hz, 40 Hz and 50 Hz). The solid lines correspond to eigenfrequencies, which were measured using the Derotator. The number of nodal lines of the corresponding eigenmodes is given by *M*. The dashed lines correspond to measurements without Derotator. The results of the measurements using the Derotator (Figure 8, solid lines) show, that if the rotation frequency increases the Eigenfrequencies of the blade increase as well, which is caused by an increasing centrifugal force. The results of the measurements, which were carried out without Derotator, show that the rotation leads to two eigenfrequencies showing the same shape of the eigenmodes (Figure 7). Hence, compared to the eigenfrequencies, which are measured using the Derotator, the eigenfrequencies measured without Derotator split up into two eigenfrequencies leading to two branches in figure 8 (dashed lines). The difference between the two frequencies depends on the rotation frequency and the number of nodal lines *M*. This effect is known as "mode-splitting". The vibration measurements show that the modes of vibration rotate at the same speed as the blade. If one measures the frequency of vibration at a measurement point that is not fixed to the rotating blade but to the lab, the detected vibration is modulated by the nodal lines passing the measurement point as it is sketched in figure 9. It can be shown [6] that "mode spitting" is caused by the modulation of the measurement signal. Hence, if one wants to determine the Eigenfrequency of a rotating object, the measurement must be performed in a coordinate system that is fixed to the rotating object.

Conclusions

A method for determining the in-plane and the out-of-plane vibrations and deflections of rotating objects is presented. The method is based on an optomechanical image Derotator, which is combined with image processing techniques and a Laser-Doppler-Vibrometry.
The results demonstrate the capability of this measurement device. As an example for out-of-plane measurements, Eigenfrequencies and deflection shapes of a rotating circular saw blade are determined. Experimental investigations show, that the deflection shapes rotate with the blade. The slippage of a roller bearing is investigated as an example of measuring in-plain motion of a rotating object using image processing methods. It is shown that the influence of the operational conditions of the bearing on the roller slippage can be identified with the method presented.

Acknowledgements

Parts of this work were supported by European Committee as a part of AI4IA (Contract No. 514510) Marie Curie FP6 and the German Ministry of Economics (AiF 14546 N).

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