Optical Vibration and Deviation Measurement of Rotating Machine Parts

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It is of interest to get appropriate information about the dynamic behaviour of rotating machinery parts in service. This paper presents an approach of optical vibration and deviation measurement of such parts. Essential of this method is an image derotator combined with a high speed camera or a Laser Doppler Vibrometer (LDV).

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, once they are interconnected with different materials, 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. This can be described by the length and direction of the displacement vector of any material fixed point during its run time.

This displacement vector, caused by the external excitations, can be split into two components. Namely into in-plane displacements which take place inside the rotational plane. They are mainly caused by the fluctuating rotational speed, which is always present. Secondly, out-of-plane displacements take place into direction of the rotational axes, mainly caused by lateral loads (Fig. 1).

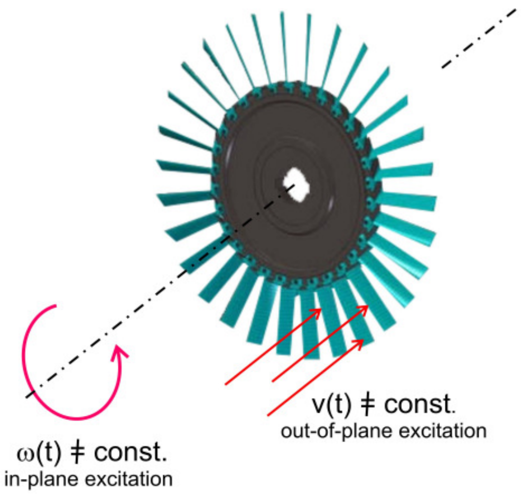

Fig. 1 Types of deformations illustrated at a turbine blade

For measuring the deformation and vibration of the rotating objects the displacement vector of any material fixed point between the relaxed position and the position of the same point under load should be determined. This vector can be defined and split relative to body fixed frame, dependent on the measurement methods (Fig. 2).

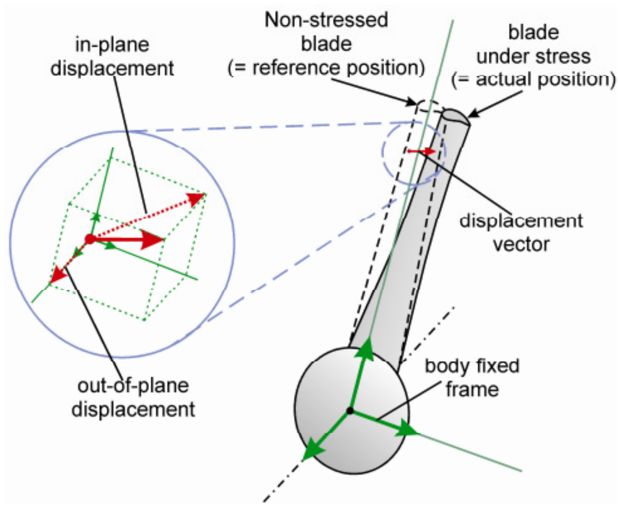

Fig. 2 Deformation splitting

There are several methods to measure the out-of-plane displacement, like holographic interferometry and Laser Doppler Vibrometry (LDV)[1-4]. Holographic interferometry is a non-contact full-field optical method. To acquire the state of vibration, a pulsed laser with pulse duration of approximately 10-30 ns will be applied. By recording the image of the object before and after deformation, an intereferometric comparison between these two states can be made. Thereby, the deformation field can be detected. Once the object is rotating between exposures, the lateral shift of the speckle pattern causes the interference fringe to disappear. But if the rotational movements of the object could be eliminated, this problem can be solved[4]. LDV is also a well-established non-contact method, commonly used for vibration measurements on static objects. However this method has a limitation for the rotating objects. Thereby the LDV signal contains periodically repeated speckle noise and a superposition of vibration velocity components. To overcome this problem, a tracking system is used[5], whereas the laser beam follows the rotating surface. The laser beam is triggered by using a position sensor. This allows that each acquisition starts at the same angular position of the rotating object. However, the measurement is not continuously.

For in-plane measurement of the displacement, speckle techniques and image processing will be used[6,7]. By image processing methods, the image sequence of rotating object is recorded by the use of stroboscopic light (illumination and camera triggered by each other) or by a high speed camera. By means of the stroboscopic method only periodic vibration can be recorded and just one image acquisition per rotation or flash is possible. By applying a high speed camera, many pictures can be saved indeed, but separating the rotational and the transnational motion by image processing algorithms is very difficult to perform. One Solution represents the image derotator technique with a high speed camera.

The speckle method however has some disadvantages, such as the time-discrete character of the measurement or the limit of measurerment range due to the light source. Another disadvantage of this technique is a low resolution of speckle-images. Therefore, this technique is not applicable in the industrial environment and on technical surfaces.

Due to the mentioned disadvantages, it is beneficial to eliminate the rotational movements to investigate only the displacement vector in the body fixed frame. This will be realized by the use of LDV and high speed camera with an image derotator (Fig. 3).

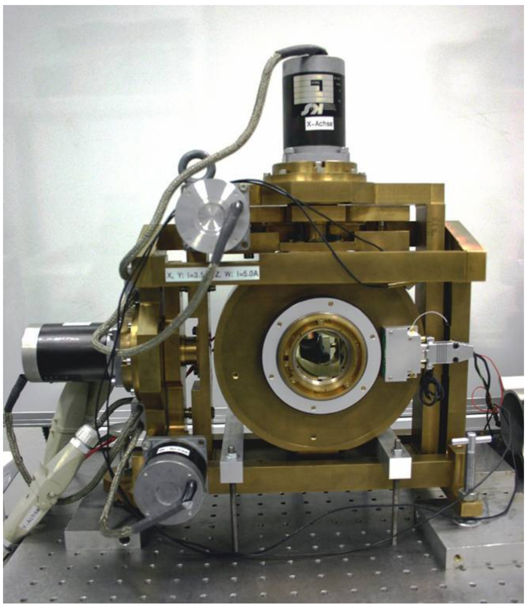

Fig. 3 Image derotator

The main component of the derotator in our case is a dove prism. During rotation of the prism around its length axis, the image generated through the prism rotates at twice of the prism rotation rate (Fig. 4). This type of prism is used to eliminate the object rotation visually. To receive an optimally derotated image, the optical axis of the prism, the rotary axis of its drive and the rotary axis of the object should be identical and 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 that affects the rotary motion (Fig. 3).

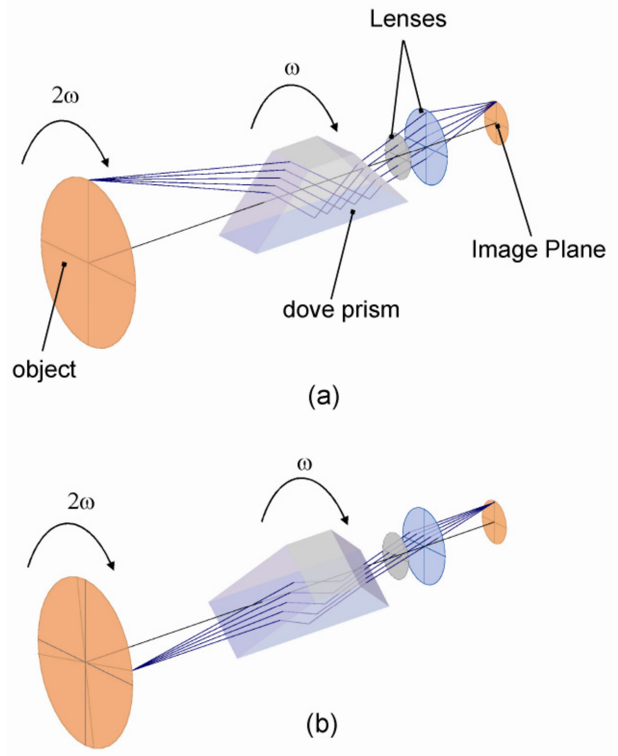

Fig. 4 Optical path through the dove prism for 2 different rotation angles (a) object rotation angle 2ω = 0° (b) object rotation angle 2ω = 80°

For measuring the in-plane deviations, a certain image processing technique is applied. Fig. 5 shows the experimental set up which is used for in-plane measurements. The object image is captured from the derotated object by a high speed CMOS-camera with a variable resolution and picture frequency.

As an example for in-plane measurement, the dynamic slippage behaviour of roller elements during bearing operation will be introduced. Slippage happens if there is a difference between the theoretical rotational frequency of the roller elements and their actual rotational frequency. Unsteady skidding motions enforce 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[8]. During further operation of the bearing, fatigue and cracks develop at the raceways. Resulting damage affects the operational behaviour and noise emission of bearing significantly as well as bearing breakdown after short operation time[9]. Up to now, a limited range of slippage measuring methods for bearings exist[9-12]. Unfortunately, they are complex to apply and only suitable for a small number of bearing types, especially for big-sized bearings (30-60 mm roller diameter)[9, 10]. The majority of bearings in industrial applications have smaller dimensions, which are difficult to examine with these methods.

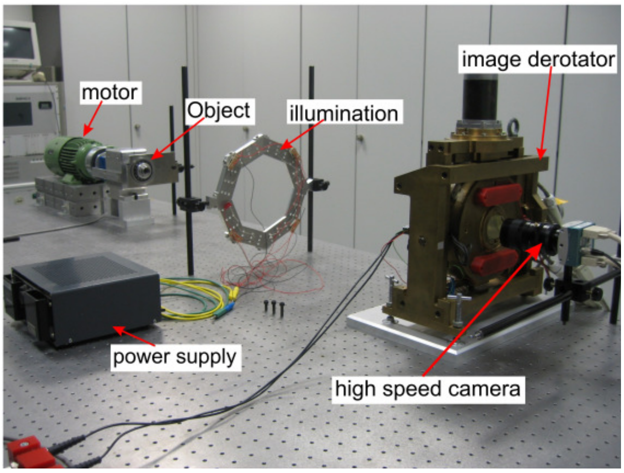

Fig. 5 In-plane experimental setup

In this experiment, the dove prism rotates with half of the rotational frequency of the bearing cage f_c. So it is possible to receive a stationary view of the cage and the possibility to observe the rotational movement of the roller elements. The real rotational frequency of the roller elements f_{re} can be determined from these images. The rotational frequency of the roller elements f_{re} will be determined by tracking the movement of geometric features at the roller elements, using sequential images. These images are captured by a high speed camera during bearing rotation (Fig. 6).

First, the contrast, brightness and intensity of the images will be adjusted by using digital image processing techniques. Intensity adjustment is an image enhancement technique that maps an image's intensity values to a new specified range such that certain features will be easier to see. Some roller elements of the bearing are marked by laser ablation (Fig. 6). The velocity of a feature that is identified on 2 sequential images can easily be obtained by dividing the distance it has covered by the time lag between the 2 images. To track these marks, a template matching method, based on correlation, will be used.

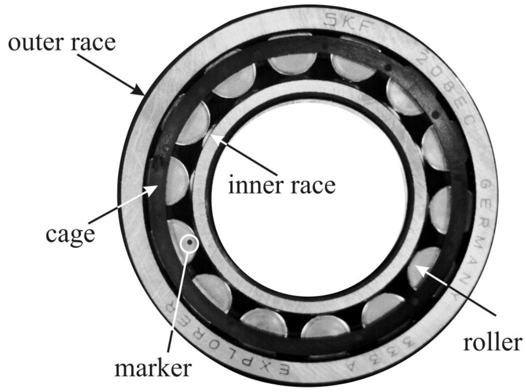

Fig. 6 Image acquisition at a roller bearing with a high speed camera

In order to detect the out-of-plane displacements of rotating objects, the same experimental set up as for the in-plane measurement is used (Fig. 7). Instead of the high speed camera, a scanning LDV is applied. This system allows collecting automatically vibration data from a user-defined area at the investigated object. A rotating cut off disc is used as object. A magnet exciting system is used for applying the out-of-plane displacement. In practice, the out-of-plane excitation is mainly caused by cutting operations. The diameter of the cutting disc is very often more than one meter. The lateral vibration is in the micrometer range. The main problem here is that the cutting line diverges with respect to a desired straight line due to interaction between the wheel and the workpiece. The phenomenon depends greatly on the stiffness, damping characteristics of blade and machine settings. Knowledge about the cause of a cutting deviation allows designing a thinner steel blade. It leads to less cutting loss and increased material resource efficiency. Also, with the same thickness of tools it is possible to increase the rate of removed material.

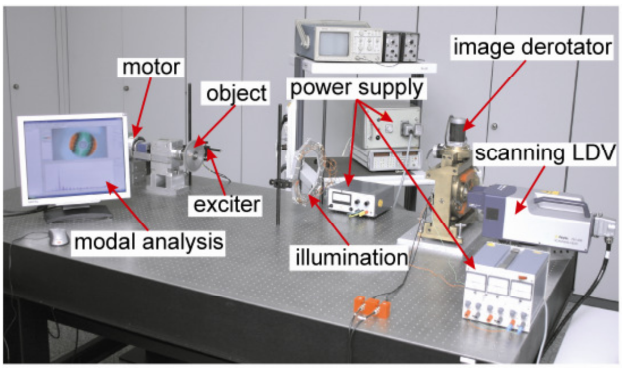

Fig. 7 Out-of-plane experimental setup

In the experimental setup on the motor axis (Fig. 7) a cutting wheel is mounted. The wheel rotates during measurement under constant excitation at a natural frequency. By means of a scanning LDV, the full surface of the cutting wheel is measured. At first without the image derotator (Fig. 8), then the dove prism of the derotator rotates with the half of the rotational frequency of the wheel.

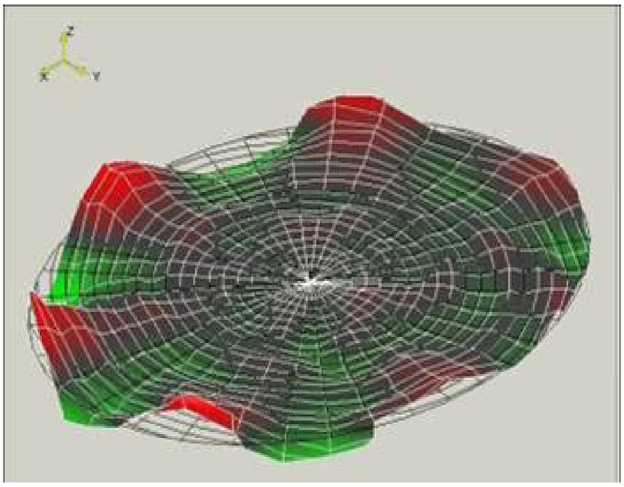

Fig. 8 Rotating cut off wheel, without an image derotator exited at 608,8 Hz, measured with a scanning LDV

The laser point of the LDV is directed on the surface of the cutting wheel through the image derotator. This means, that a laser point of the LDV is located on the same position during the measurement of a defined point on the wheel, while it is being rotated. Thus, the whole surface of the cutting wheel is scanned by point to point in a quasi stationary state (Fig. 9).

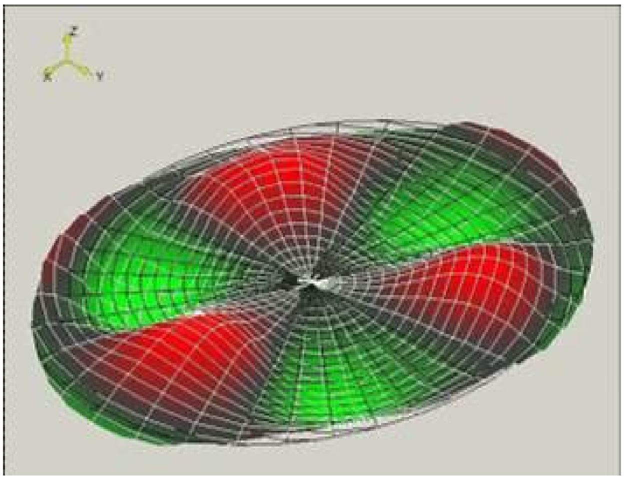

Fig. 9 Rotating cut off wheel, with an image derotator exited at 608,8 Hz, measured with a scanning LDV

As displayed in the Fig. 9, the mode of vibration and the frequency of the rotating cutting wheel can be detected clearly by use of the image derotator and scanning LDV. Without the image derotator (Fig. 8), overlapping image information due simultaneous vibration and rotational movement will be displayed.

Due to a number of advantages, image derotating techniques are a practical solution to analyze the dynamic behaviour of rotating objects. It allows high rotating object as stationary to display, thereby it is possible by use of the camera technique or LDV the components of displacements laminar and continuous to display.

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