

A new method for measurement of rotating objects utilizing Laser Doppler Vibrometry combined with an optical Derotator with focus on automotive applications

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Abstract

For more than 20 years Laser Doppler Vibrometry (LDV) is an established tool in vibration engineering for non-contact vibration measurements. The LDV method is not only limited to measurements on single test points. Utilizing a pair of galvano-electrical mirrors for steering the laser beam in x and y directions across the surface the vibration pattern of full areas can be mapped. Such scanning LDVs (SLDV) have found many applications in the automotive industry as well as in institutional research. However the use of the SLDV technology is limited to stationary objects and rotating objects with smooth uninterrupted structures such as brake discs or tires. Up until now measurements on objects with complex non-continuous structures such as bladed discs, fans, propellers have not been possible yet. Furthermore, interpretation of travelling non-stationary modes which can be found on rotating tires, saw blades etc. has been difficult with conventional SLDV technology.

A Derotator is an optical unit overcoming this limitation by maintaining a fixed position of the SLDV laser beam in the rotating coordinate system of the test object. By “derotating” the object with a rotating optical unit a stationary image of the object is achieved and a standard SLDV measurement can be done where the laser beam location on the objects remains stationary. Like in usual SLDVs, the system is acquiring data in one point then moves to the next scanning point and so on.

By means of measuring the vibration behavior of a rotating object during an engine run up critical rotational speeds and resonance frequencies of the rotating object can be identified. Furthermore material stiffness changes caused by centrifugal forces can be visualized analyzing the Eigenfrequency changes in a waterfall or Campbell diagram.

In this paper the basic principle of a derotated SLDV measurement is explained. In the first application presented in this paper the Operational Deflection Shape (ODS) of a rotating disk is measured with and without derotating and the differences in the results are analyzed.

In the second application a typical measurement procedure doing a trouble shooting on a pump rotor will be elucidated. Finding the critical rpm and the corresponding ODS clearly shows the reason for the failure in operation conditions.

1. Introduction

The basis of Laser Doppler Vibrometry has been laid in the 1960s with different publications [1-3]. Probably the first reference in book format is L. E. Drain’s book “The Laser Doppler Technique” [4]. Subsequently LDVs have become a valuable tool for accurate non-contact measurement of vibration on different sized structures.

In fact, the LDV method is not limited to measurements at single test points. By 1984 the research group of the German car manufacturer Volkswagen AG [5] built a full area scanning LDV (SLDV). Utilizing a pair of galvano-electrical mirrors the laser beam can be steered in x and y direction which allows a scanning measurement of points on the surface of an object. As a result of such a scanning measurement the out of plane vibration behavior of the object is obtained.

Using the SLDV technique up until now only continuous rotating objects like brake disks could be measured under rotation. Segmented parts like propellers and rotor blades could not be examined under rotation and so only could be investigated using experimental modal analysis and measuring the frequency transfer function (FRF) for non-rotating conditions. The real excitation under operating conditions is quite different from a modal test at standstill and is moreover hard to simulate exactly. Stiffening effects by centrifugal forces also influence the result under working conditions. It is therefore mandatory to measure segmented parts in rotation.

With a special rotating optical unit whose rotation speed is synchronized to the object rotation it is now possible to “derotate” the rotating object and measure the ODS.

With SLDV stationary modes as well as modes travelling are detected on continuous rotating objects such as a rotating tire, brake disc or similar. The interpretation of the travelling modes has been a matter of discussion since longer time. SLDV combined with “derotation” and a laser beam travelling together with the modes will provide deeper insight into this matter. Further benefits of “derotating” the laser such as reduction of repetitive noise (Speckle noise) and avoiding mode splitting are discussed hereafter.

2. Principle of a SLDV

The LDV is a non-contact velocity and/or displacement transducer, which can be used to measure the vibration of an object. The LDV focuses a laser beam onto the measurement object. The object scatters or reflects a part of the laser light back to the LDV. When the measurement object is moving with a certain velocity v the frequency f and phase of the back-scattered light is shifted by means of the Doppler Effect.

$$f = \frac{2 \cdot v}{\lambda} \quad (1)$$

To detect the frequency (which is proportional to the object velocity) and/or the phase shift (which is proportional to the object movement) of the back scattered laser light caused by the Doppler Effect a heterodyne Mach-Zehnder-Interferometer (Figure 1 – framed part) is used in connection with a photo detector [6]. By means of a further post processing, which basically includes the frequency and/or the phase demodulation of the electrical signal coming from the photo detector, the velocity and/or the displacement is provided.

In a SLDV two servo controlled galvano-electrical mirrors (Figure 1 – Scanner mirrors) steer the laser beam very accurately in x and y direction over the structure. By means of pre defining scan points in a teaching process an automated scan, measuring the vibration behavior of each scan point, can be done.

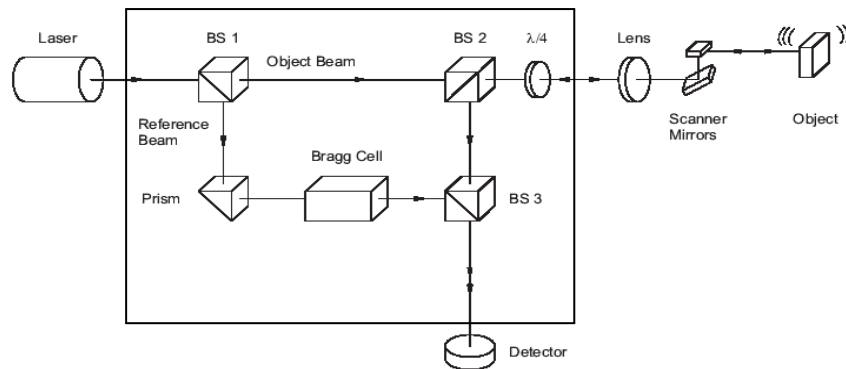


Figure 1. Optics scheme of a SLDV measurement head

2.1 Principle of a SLDV measurement using a “Derotator”

To measure a rotating object with the SLDV technique does not necessarily require a “derotator”. On a continuous surface such as a belt pulley or drive shaft SLDV’s are routinely used. However as soon as the surface is interrupted (wheel, fan, bladed disk) the standard SLDV method will fail. The laser beam measuring the vibration of each scan point needs to follow a fixed position on such a rotating object. With the existing SLDV system there were two possibilities to follow the rotating object:

1. Steer the laser with the scanner mirrors so that the laser follows the same position on the rotating object. This method has been successfully tested for relatively slow objects such as ship propellers [7]
2. Derotate the rotating object using an external optical unit which rotates itself synchronized to the object RPM to let the object seem to stand still [8,9]

The first method has the drawback that the maximal possible RPM of the object is limited due to the limited speed of the scanning mirrors solution. As shown in figure 2 an external optical unit called “Derotator” is positioned in front of the standard SLDV sensor. In the Derotator a “Dove Prism” rotates with half the rotational speed of the rotating object to let the object seem to stand still for the SLDV sensor head.

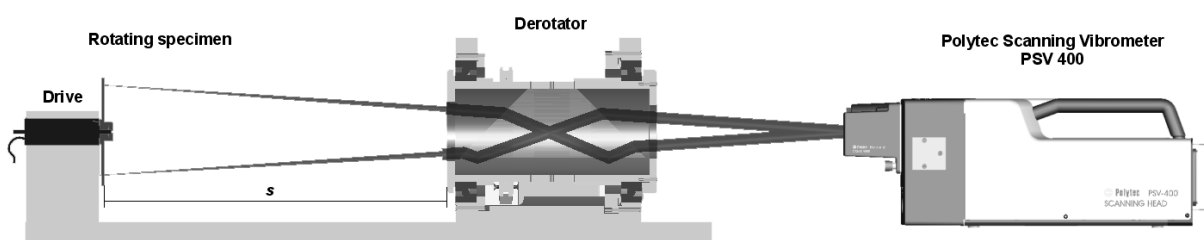


Figure 2. Principle of derotating a rotating specimen using an external rotational unit called “Derotator”

By rotating the Dove-Prism in the Derotator about 90° the image of the object gets rotated by 180° (see Figure 3). To synchronize the rotational unit of the Derotator with exactly half the object RPM a PID controller is used. By processing an external encoder signal from the object and an internal encoder signal from the internal driving motor of the optical unit the PID controller delivers a certain voltage to the driving motor to set the Derotator RPM. By means of using different PID values which are predefined in different mode settings constant RPMs and also high accelerations as in run-ups can be synchronized.

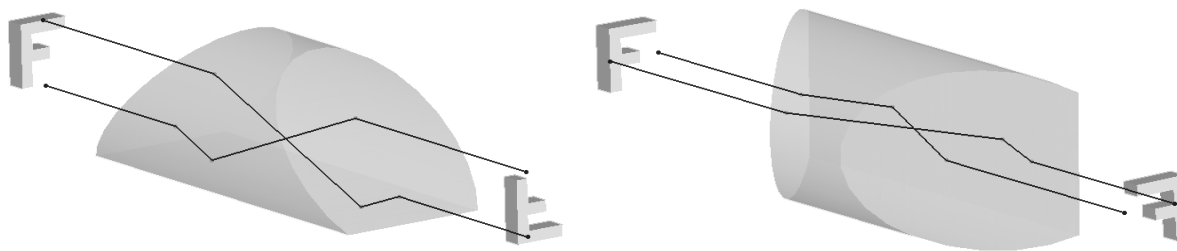


Figure 3. Optical imaging with a “Dove-Prism”

During a scanning measurement with the Derotator the laser of the SLDV will be positioned with the scanning mirrors at each of the pre-defined scan points in order to measure the vibration (amplitude + phase) of each scan point over a certain time period on the derotated object. In order to get a phase relation between the individual scan points SLDV requires a phase reference which is an accelerometer or force transducer in most automotive measurement situations [10] . Naturally, in a rotating system applying such a mechanical transducer as a phase reference is either impossible or very difficult. To overcome this limitation a second non scanning laser is coupled into the Derotator. This laser is positioned onto a fixed point on the object during the whole scanning measurement recording the reference vibration (amplitude + phase). Relating the phase of each scan point to the phase of this reference point a phase relation between all other scan points is obtained and the vibration shape can be displayed as a 3d animation.

3. SLDV measurement using a Derotator – Applications

In a first example presented in this paper a disk is measured with and without derotating. A simple data CD was mounted on a driving motor with an integrated optical encoder. Before the measurement could be started the rotational axis of the Derotator had to be aligned to the rotational axis of this test object. All in all there were 4 degrees of freedom which should be aligned with the integrated adjustable tip, tilt, x and z axis (Figure 4).

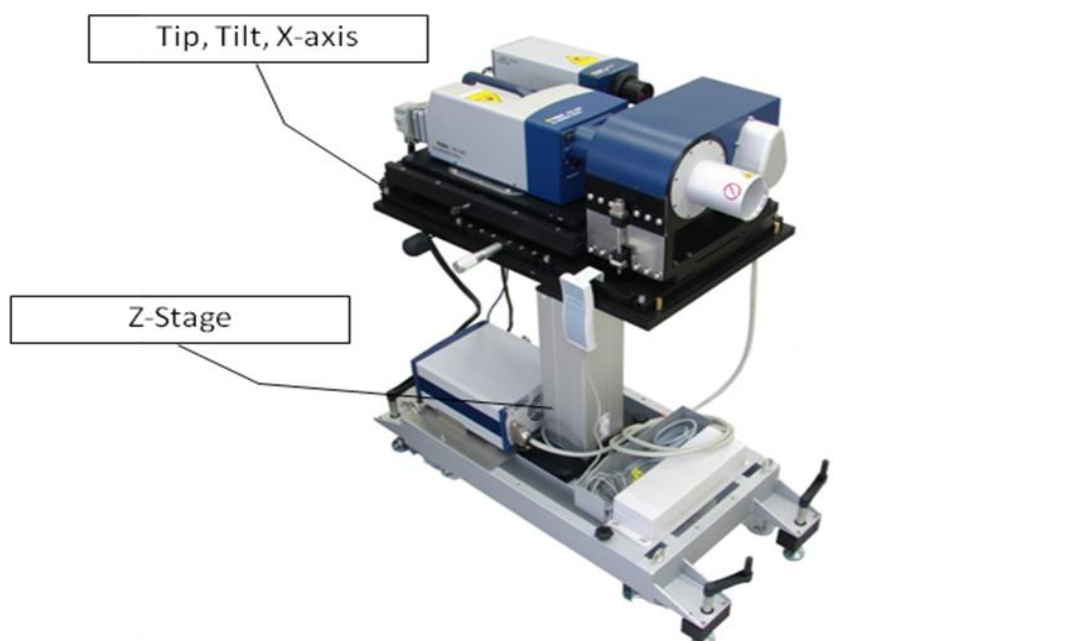


Figure 4. Setup of a complete Derotator with adjustment unit (black)

3.1 Results - Disk with and without derotation

Basically the first step of a standard procedure to analyze the vibrations of a rotating system is a run up. By means of post processing the recorded data of the run up in an order analysis the critical rotational speed of the rotating system can be found. Knowing those critical RPMs with maximal vibration amplitude one can perform a scanning measurement at the stable rotational velocities in order to get the vibration shape of those critical RPMs.

In figure 5 the Campbell Diagram for a run up with the Derotator from 0 to 12000 RPM (y-axis) is shown. Analyzing the Campbell Diagram one can see the so called “Orders” which are strait lines starting from the origin. These orders are caused by vibrations of the motor driven disk which could be generated for example by unbalances. The frequency (x-axis) of those orders increases with a constant factor ($n= 0.5, 1, 2..$) when increasing the rotation velocity. As an example taking an unbalance which causes a vibration at each revolution the frequency of this vibration will increase directly proportional to the RPM for the first and for all higher orders. Besides the order lines there are usually also vertical lines which have a nearly constant frequency over different rotational speeds – the structural resonances. Recognizing the fact that the frequencies of those structural resonances increase with an increasing rotational speed it is obvious that the stiffness of the disk is changing (increasing) due to the higher centrifugal forces. Another effect that can be seen in the Campbell Diagram is that the maximal amplitudes (red color coded) appear when an order intersects with a structural resonance.

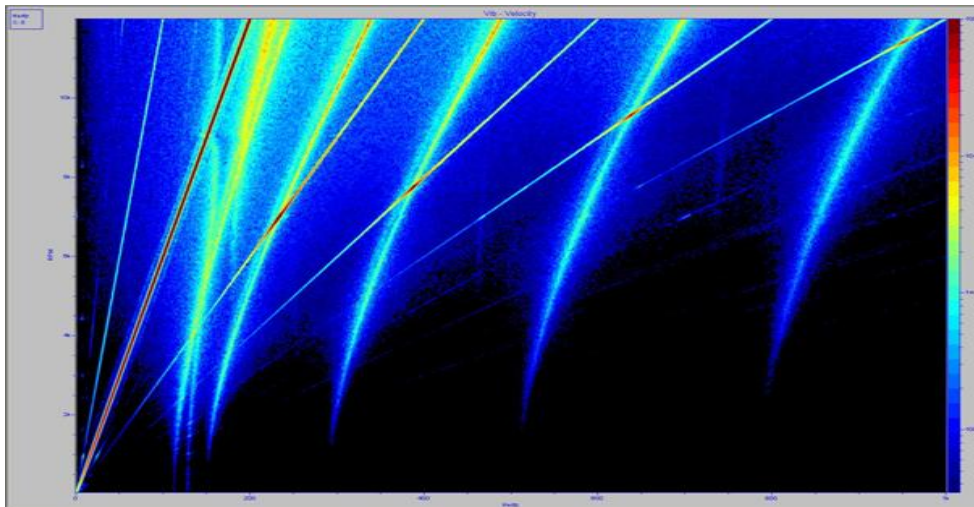


Figure 5. – Campbell Diagram of a rotating disk (0-12000RPM) with Derotator

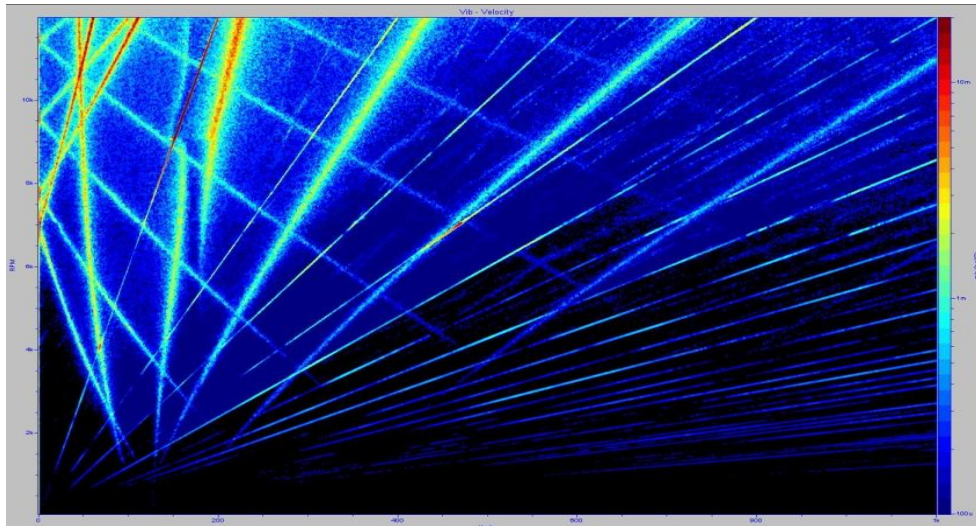


Figure 6. – Campbell Diagram of a rotating disk (0-12000RPM) without Derotator

In figure 6 the Campbell Diagram of the rotating disk without Derotator is presented. Comparing both diagrams one can see that the structural resonances which are curved lines in figure 5 are split into two curved lines in figure 6. These split curves intersect at 0 RPM at the same position as the structural resonances of figure 5.

Let's look at first at a non-rotating object: The vibration at a certain point has a given amplitude and frequency f_{vib} . Once this object rotates, the rotation causes a sinusoidal modulation of the amplitude which is proportional to: $\cos(n2\pi f_{Rot}t)$. This vibration is superposed (multiplied) onto the vibration of the object $\sim \cos(2\pi f_{vib}t)$. Using the multiplication theorem ($\cos \alpha \times \cos \beta = \frac{1}{2} (\cos(\alpha - \beta) + \cos(\alpha + \beta))$) we get two vibration terms, one with the frequency sum and one with the differential frequency.

$$* A(t) = \frac{1}{2} A \cos(2\pi (f_{vib} - n f_{rot})) + \cos(2\pi (f_{vib} + n f_{rot})) \quad (2)$$

When the rotation frequency is 0 RPM, there is no modulation of the vibration and the vibration frequency of the disk is the same for the derotated and non derotated measurement (see figure 6 intersections of the splitted curved order lines).

As an example for the scanning measurement the vibration shapes are measured at 2280RPM (figure 7 and 8). The vibration shapes 2 and 3 (with Derotator) of figure 7 is split into two branches in figure 8 due to the rotation of the disk (no Derotator). The so caused modulation of the vibration results in a vibration shape that rotates clockwise (figure 8 – deflection shape 1+3) and counter-clockwise (figure 8 – deflection shape 2+4).

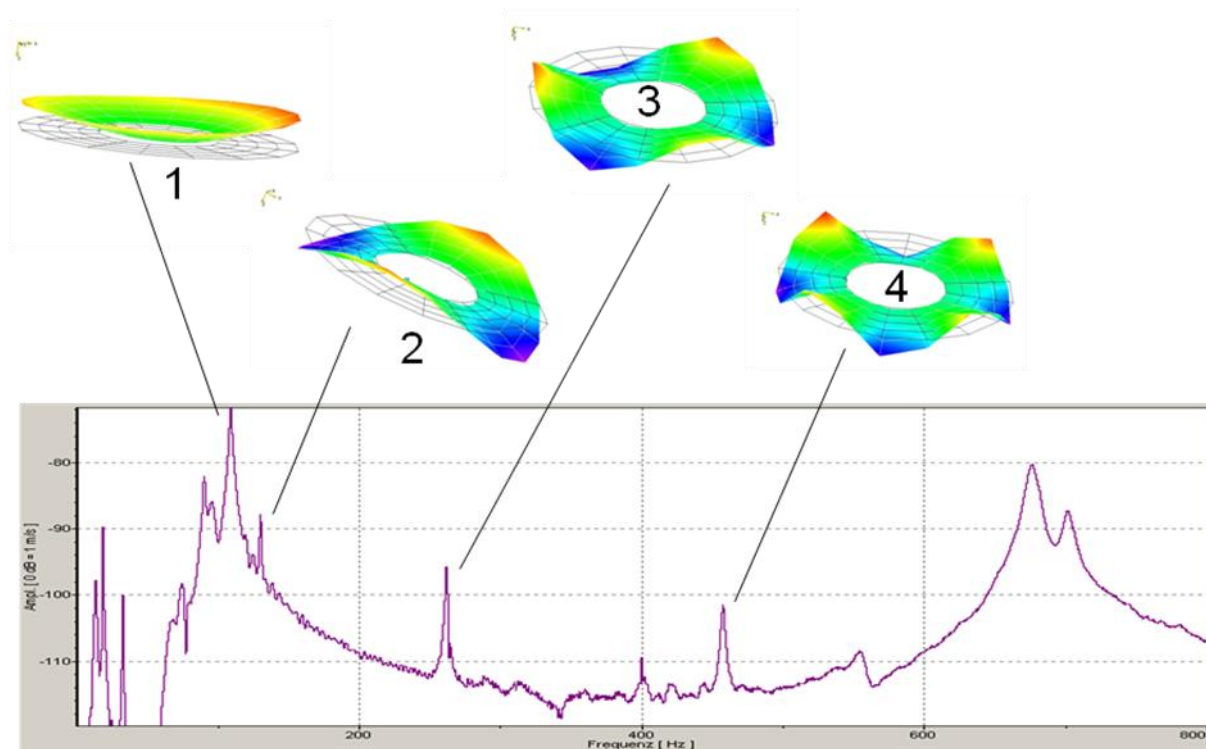


Figure 7. Spectra + Deflection shapes of a rotating disk at 2280 RPM – with Derotator

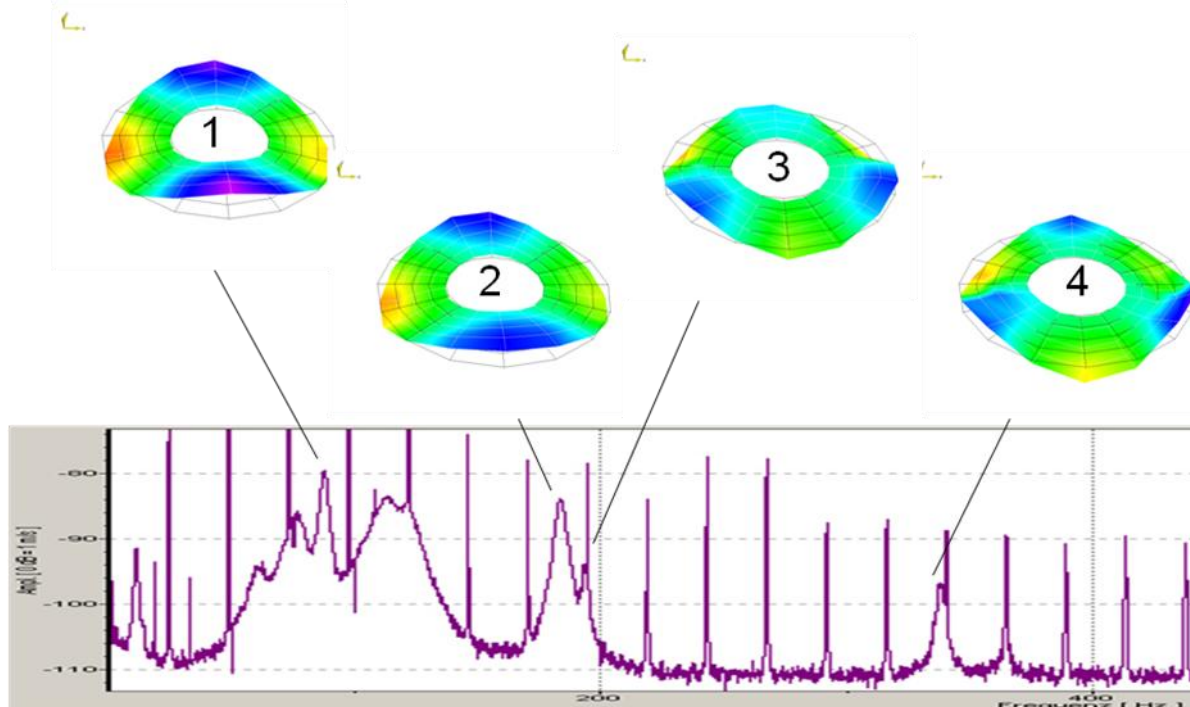


Figure 8. Spectra + Deflection shapes of a rotating disk at 2280 RPM – without Derotator

When the disc is running under the laser beam Speckles¹ are generated by means of the “rough” surface of the disk. These speckles repeat cyclically with each revolution and cause very fine peaks in the spectrum (Figure 8). Naturally in a “derotated” system these repetitive speckles cannot be found and the spectrum looks much cleaner due to the absence of these peaks.

3.2 Results – Finding the reason for failure of a rotor pump under operation

In order to find the weak point of a rotor pump in the second application presented in this paper a rotor of a pump was measured under operating conditions. The first step of the measurement was again performing a run up. By means of processing the recorded run up data in a Campbell Diagram (Figure 9 - left) the critical rotation speed (with maximal amplitude) could be pointed out to be about 3800 RPM. In the second step of the trouble shooting process a scanning measurement at 3800 RPM was done with the Derotator. In the resulting deflection shape at 5800Hz (figure 9 – right) the weak point (red marked ellipses) of the system gets clearly visible. Failure is due to fatigue at these points.

Using these measurement data the design engineer of the pump can update his FE model. Using the corrected FE model the design engineer can apply selective changes to the design to improve the lifetime of the pump and to prevent the rotor damaging.

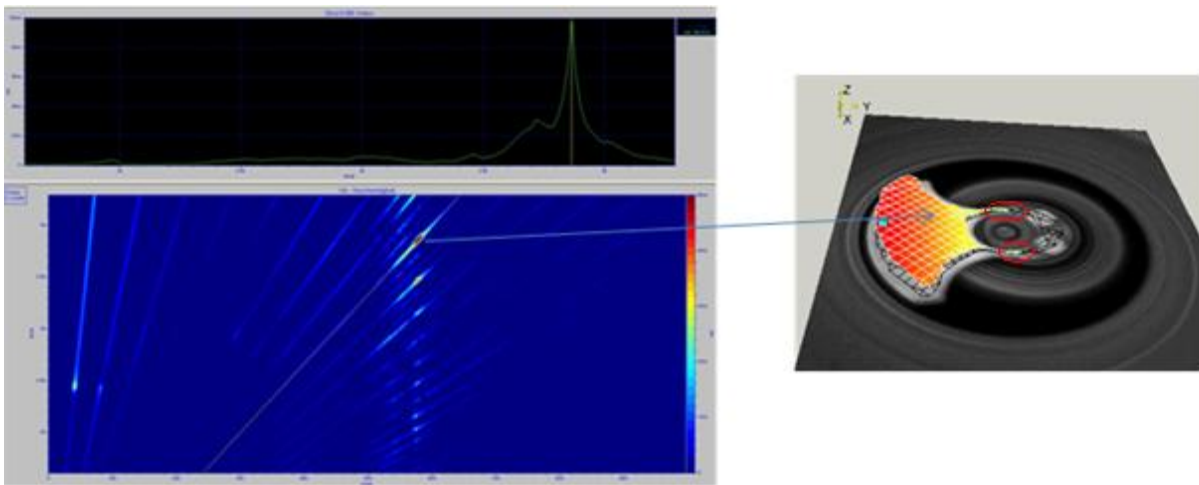


Figure 9. Campbell Diagram and deflection shape of a rotating pump

¹ When coherent light (laser light) hits a rough surface the intensity of the back scattered light is a random distribution of dark and bright fringes, the so called speckles. Speckles occur due to the fact that laser light scattered back from different positions of the laser beam interfere in space. Depending on the phase of the interfering beams the resulting speckle is bright or dark.

4. Summary and Conclusion

With the optical Derotator it is now possible to measure the Operational Deflection Shapes of most rotating objects. With an optical unit, which basically includes a Dove Prism, with half the rotational speed of the object, the rotating object virtually stands still for the SLDV sensor head and a standard scanning measurement can be done. Using these data of the scanning vibration measurement enables the design engineer to update his FE simulation. Without such measurement data it would be hard for the design engineer to find the real excitation under working conditions and also to assess certain effects that occur under rotation like stiffening of the object due to centrifugal forces. After the prototype of a Derotator has been successfully tested we will now investigate further applications for which standard SLDV's are already used such as disk brakes and tires. These results will be published in future papers.

REFERENCES

1. Y. Yeh and H.Z. Cummins, Localized Fluid Flow Measurements with an He-Ne Laser Spectrometer, *Applied Physics Letters*, vol 4, n°10, 1964
2. R. D. Kroeger, Motion Sensing by Optical Heterodyne Doppler Detection form Diffuse Surfaces, *Proceedings of the IEEE*, Feb. 1965.
3. H. A. Deferrari, R. A. Darby and F. A. Andrews, Vibrational Displacement and Mode-Shape Measurement by a Laser Interferometer, *the Journal of the Acoustical Society of America*, Vol. 42, n°5, 1967
4. L. E. Drain, *The Laser Doppler Technique*, Wiley, 1980
5. B. Stoffregen, A. Felske, Scanning Laser Doppler Analysis System, SAE Paper No. 850327, 1985
6. F. J. Eberhardt and F. A. Andrews, Laser Heterodyne System for Measurement and Analysis of Vibration, *the Journal of the Acoustical Society of America*, Vol. 48, n°3, 1970
7. P. Castellini and C. Santolini, University of Ancona, Vibration measurements on blades of a naval propeller rotating in water with tracking laser Vibrometer, *Measurement*, Volume 24, Issue 1, July 1998, Pages 43-54
8. Giancarlo Pedrini and Hans J. Tiziani, Double-pulse electronic speckle interferometry for vibration analysis, *Applied Optics*, Vol. 33, Issue 34, pp. 7857-7863 (1994)
9. W. F. Fagan, M. -A. Beeck and H. Kreitlow, The holographic vibration analysis of rotating objects using a reflective image derotator, *Optics and Lasers in Engineering*, Volume 2, Issue 1, January-March 1981, Pages 21-32
10. M. Johansmann and J. Sauer, A new tool for three- dimensional non-contact vibration measurements in automotive applications, *SAE Paper No. 2005-26-052*, 2005