The Removal of Speckle Noise from Torsional Laser Doppler Vibrometer Signals in Machine Health Monitoring

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Abstract
The torsional vibrations of a rotor can provide invaluable information with regards to the structural health of the rotor itself and its subcomponents such as rotor blades. Rotor angular measurement instruments such as shaft encoders and toothed wheels are very well suited to this application although these instruments may present difficulties with regards to physical installation. Torsional Laser Doppler Vibrometers (TLDVs) in contrast allow the measurement of rotor torsional vibrations without the need of any physical installation on the rotor, making the sensor very attractive for mobile monitoring applications. TLDVs are however greatly affected by speckle noise which is pseudo-random in nature. Since the speckle pattern is repeated for every shaft revolution, this results in the noise being manifested in the output signal at the rotor speed and its harmonics over a large frequency range. This can be detrimental towards the detection of low level torsional vibrations in the signals and as such, a technique is required to remove these effects from the measurements. In this paper various techniques are discussed that can be applied to accomplish the removal of speckle noise from TLDV measurements. From experimental testing on a laboratory test rotor, the effectiveness of the considered techniques is evaluated.

Keywords: Torsional vibrations, Laser Doppler vibrometer, speckle noise removal

1. Introduction

Users of turbo-generators such as found at power stations are faced with various issues related to rotor blade health. One such issue concerns the torsional excitation of the rotor in the form of impulses exerted by the generator due to electrical grid disturbances. As a result blade modes that couple with rotor torsional modes are excited by these impulses. This in turn affects the remaining life of especially the more flexible blades in low pressure turbines [1]. Thus it is important to have knowledge of the occurrence frequencies of these events as well as the severity of blade natural frequency excitation.

Several techniques exist to measure turbomachinery blade vibrations and are mainly divided into direct and indirect techniques. Direct blade vibration measurement techniques include strain gauge installation directly on blades, blade tip time-of-arrival measurements [2] and Eulerian laser Doppler vibrometry [3]. Blade vibrations can indirectly be obtained by means of shaft torsional vibration measurements, although the prerequisite for this is that at least one of the blade modes of interest should couple with shaft torsion [4], which is the case here. Torsional vibration measurements on rotors can in turn be acquired using strain gauge telemetry systems as well as rotary encoders where the latter may employ a shaft encoder, toothed wheel or zebra strip. Strain gauge telemetry systems and rotary encoders have the disadvantage though that they require a stationary rotor for both installation and troubleshooting, which generally is not a readily available option at power stations. This limitation can however be overcome with the use of a torsional laser Doppler vibrometer (TLDV) such
as the Polytec 4000 series rotational vibrometer, which employs two parallel laser beams to obtain the torsional vibration signature [5].

TLDVs nevertheless suffer from the speckle noise phenomenon which significantly reduces the instruments’ signal to noise ratios (SNR). A speckle pattern is formed when light from a coherent light source (such as a laser beam) shines onto an optically rough surface and consists of a random distribution of light and dark spots. When the target surface moves perpendicular to the laser beam, the speckle pattern undergoes translation, boiling or both. This leads to Doppler signal amplitude modulation as well as phase modulation of the demodulated TLDV output, both in a random fashion [6]. The latter mechanism is a significant contributor to signal noise. A rotating target represents a worst case scenario as far as speckle noise is concerned [7]. In such an application the random speckle pattern is repeated once per revolution, resulting in the noise having a pseudo-random nature. This leads to relatively equal amplitude peaks in the frequency spectrum at the first rotor order up to the high order harmonics, and is indistinguishable from genuine vibration information [7].

In order to reduce the effects of speckle noise in TLDV measurements, several experimental and post-processing approaches can be followed. One experimental approach is to randomize the axial measurement position of the TLDV, which serves to destroy the periodicity of the speckle pattern. This can be accomplished in a controlled manner by means of TLDV scanning [8] or by operating the instrument in a hand-held fashion [9]. A second approach is to apply an oil film at the axial measurement location which optically distorts the speckle pattern randomly [8].

In terms of post-processing approaches, it is possible to remove the order domain content of rotating equipment signals by means of angular domain (AD) fast Fourier transform (FFT) editing [10]. This approach firstly entails converting the time domain signal into the AD. Using a complex FFT, the order peaks are manipulated by setting them to the complex minimum of the adjacent FFT sample values. After obtaining the modified AD signal by means of inverse FFT calculation, the signal is converted back into the time domain. The resulting spectrum thus excludes order domain content with the remaining spectrum content unaffected. It must be noted that the total AD record length should contain an integer number of periods of the fundamental frequency. All harmonics of the periodic signal will then be located at single lines in the resulting FFT [11].

This paper is concerned with evaluating the different experimental and post-processing techniques discussed above in order to identify a suitable approach for industrial implementation. In order to accomplish this, tests were conducted on a simple laboratory test rotor as explained in the next section.

2. Experimental setup

The test setup is shown in Figure 1 and consisted of a ø31 mm solid steel shaft with two ø150 mm disks between two rolling element bearings. The rotor was driven by a speed controlled motor and the drive end (DE) disk was installed with eight 120 mm long, 2 mm thick flat blades. No blades were installed on the non-drive end (NDE) disk.
Stationary impact modal tests were conducted on the rotor and blades in order to identify the rotor torsional natural frequencies as well as the coupling blade natural frequencies. Each blade was tested individually using a small impact hammer as excitation and a laser Doppler vibrometer as transducer. Similarly, the rotor was excited with a small impact hammer at various points along the shaft and responses were measured with accelerometers. In Figure 2 the average frequency response function (FRF) of the blades is compared to the average rotor torsional FRF. Predominant peaks are noted in Figure 2(a) and (b) around 145 Hz, 152 Hz, 334 Hz and 507 Hz. To gain insight into the rotor behaviour at these frequencies, modal analyses were performed on the data. It was revealed that the 1st and 2nd blade bending modes couple with rotor torsion at 152 Hz and 332 Hz. The additional peaks visible in Figure 2(b) at 101 Hz and 198 Hz correspond to the 2nd order rotor torsion modes of the brake disk and NDE disk respectively.

A Polytec OFV4000 TLDV was the instrument used for evaluating the various speckle noise reduction approaches. A Binsfeld Rx10k telemetry system with strain gauges as well as a 235 pulse per revolution (PPR) zebra strip was installed close to the TLDV measurement location to serve as references. An Optel-Thevon 152G8 optical sensor was used to pick up the pulses from the zebra strip. The sensor locations are shown in Figure 3. Data capturing was performed with an OROS OR35 system utilizing the NVGate 7.2 software.

Initially it was envisaged to utilize a hydraulic brake system at the rotor end to excite the rotor torsionally. However, the system’s response was found to be too slow to excite the rotor assembly’s natural frequencies sufficiently. Using instead a cap screw protruding from the shaft at the brake disk to strike a 1.8 kg hammer during rotation was found to perform this task, although in a crude manner. As repeatability of the impact force would be of low quality, average results for typically 10 impacts are considered in this paper. Power spectral densities (PSDs) of the average strain and torsional vibration (as obtained from the respective reference sensors) are shown in Figure 4 and peaks corresponding to Figure 2 are clearly
noticed, showing the excitation technique to be effective. The predominant peak in Figure 4 at 300 Hz is noted to be caused by the electric motor.

Figure 2: Average FRFs

Figure 3: Sensor locations
Tests were conducted at 600, 900, 1200 and 1500 RPM for three measurement conditions namely 1) normal measurement, 2) TLDV scanning and 3) oil-film application. TLDV scanning was accomplished by controlling a servo-actuated horizontal stage of the tripod supporting the TLDV from LabView using 10 s pseudo-random driving signal. The results are discussed in the following section.

3. Results

3.1. Experimental approach

Figure 5 compares the PSDs obtained from (a) TLDV scanning and (b) oil film application to that obtained from normal measurements at 600 RPM. It is observed that both approaches reduce the rotor speed harmonic peak levels significantly. Both approaches also exhibit increases in overall noise floor levels which are detrimental to the SNRs. Some activity around 150 Hz is visible in Figure 5 (a) but not around 340 Hz. Both peaks are visible in Figure 5 (b) although peaks not identified from modal testing are also seen. The results at 1500 RPM are presented in Figure 6 and it is noted that the peak frequencies of interest are not sufficiently captured by any of the three measurement conditions.
Figure 5: Experimental results at 600 RPM

Figure 6: Experimental results at 1500 RPM
3.2. Combined experimental and post-processing approach

Next the effects of AD FFT editing are considered in Figure 7 and Figure 8 for the different measurement conditions at 600 RPM and 1500 RPM respectively. From Figure 7(a) it is gathered that AD FFT editing is very efficient for normal measurement conditions. AD FFT editing does slightly improve the results from TLDV scanning and oil film application, although the increased noise floor from these measurement conditions still presents the main limitation.

From Figure 8 the same conclusions are reached. It is however noted from Figure 8(a) that the higher rotor speed does reduce the capability of detecting the frequencies of interest, although they are still visible. This observation is validated by evaluating the speckle noise root mean square (RMS) levels at the different rotor speeds (Figure 9).

Speckle noise RMS levels of the considered measurement conditions are compared in Figure 9(a) and (b) at different rotor speeds prior and subsequent to AD FFT editing respectively. From Figure 9(a) it is observed that the RMS levels increase with rotor speed for normal measurement conditions as well as TLDV scanning. Speckle noise RMS levels from oil film application measurements appear to be uncorrelated to rotor speed. Figure 9(b) demonstrates the efficiency at which AD FFT editing reduces speckle noise.

![Figure 7: Post-processing results at 600 RPM](image-url)
3.3. Various encoder options

From the previous section, it is clear that the results from AD FFT editing of a signal obtained in a normal manner, outperforms those from the experimental speckle noise reduction techniques considered in this paper. However, this was achieved with a 235 PPR zebra strip encoder which allows one to accurately obtain instantaneous rotor speed for AD
transformation. Since it is rarely feasible to install rotary encoders on industrial machinery, the question is raised of whether it is possible to obtain satisfactory results using a 1 PPR tachometer signal or, ideally, no tachometer signal at all. The 1 PPR tachometer signal was obtained from the normal measurements in the previous section by considering only the reference pulse of the zebra strip encoder.

An approach exists where an acceleration signal of a gearbox can be used to extract instantaneous shaft speed information [12]. With this approach, rotor harmonic peaks are band-pass filtered and instantaneous shaft speed is then obtained from frequency demodulation. However, satisfactory results could not be obtained when applying this approach to the measurements considered in this paper.

Instead an approach was followed which works on the assumption that the speckle noise pattern is indeed purely pseudo-random and cyclostationary throughout each measurement. Using a part of the signal that is devoid of external torsional vibration excitation and that spans at least one shaft revolution, correlation coefficients between the reference signal and the remaining signal are calculated in the time domain using a sliding window. Since it is assumed that the speckle pattern repeats itself at each shaft revolution, the correlation coefficient will peak each time the measured signal correlates with the reference speckle pattern. These peaks are then treated as synthetic 1 PPR tachometer pulses. It is inherently assumed that the speckle noise signal distortion in the time domain as a result of rotor speed fluctuation is negligible, which implies a limitation on speed fluctuation for this approach to perform effectively.

Figure 10 compares the rotor speed signatures at 600 RPM extracted from this synthetic speckle noise tachometer (SNT) to that from the zebra strip tachometer signal and it is seen that these two signals correlate very well. It is also clear that the rotor speed resolution obtained from the speckle noise tachometer is considerably coarser than that from the zebra strip tachometer signal. This is because the TLDV signal was sampled at a lower rate than the zebra strip signal. To investigate whether any advantage can be gained by artificially refining the SNT rotor speed resolution, the SNT rotor speed signature was low-pass filtered in the angular domain and the modified SNT signal was then obtained via integration.

Figure 11 compares the PSDs obtained after performing AD FFT editing at 600 RPM using the three tachometer signatures discussed above, to that obtained from AD FFT editing using the 235 PPR zebra strip encoder signal. It is seen that the 1 PPR zebra strip tachometer signal yields results almost identical to that from the 235 PPR zebra strip encoder signal (blue curves). The SNT signal’s results are significantly noisier, although still yielding an improvement from the unedited PSD (Figure 7a). It is noted that the filtered SNT signal does indeed show some improvement on the unfiltered SNT signal results.

In Figure 12 the PSDs are compared at 1500 RPM. It is observed that the 1 PPR zebra strip tachometer signal result is still very close to that from the 235 PPR zebra strip encoder signal, although less so than the results at 600 RPM. Both the unfiltered and filtered SNT results are significantly better at the higher rotor speed and compare very well with the 235 PPR zebra strip encoder results. This is a direct result of a finer rotor speed resolution being available due to the higher rotor speed. The filtered SNT results show slight improvements on the unfiltered SNT results.
Figure 10: Rotor speed signal comparison using 1 PPR zebra tacho signal and SNT signal

Figure 11: Post-processing results at 600 RPM
Figure 12: Post-processing results at 1500 RPM

Figure 13(a) and (b) compare the speckle noise RMS levels for the different encoder signals at various rotor speeds prior and subsequent to AD FFT editing respectively. It is observed that the alternative encoder signals give comparable results to the 235 PPR zebra strip encoder.

Figure 13: Average speckle noise RMS comparison
4. Conclusions

In this paper different experimental and post-processing approaches were considered towards the reduction of speckle noise and its effects on TLDV measurements. It was found that experimental speckle pattern randomization using pseudo-random TLDV scanning as well as oil film speckle pattern distortion are effective in reducing speckle noise related harmonic peaks in the measured spectra. However, at the same time these two approaches increase the measurement noise floor thereby reducing the SNR significantly which is detrimental towards detecting the low vibration levels associated with the coupled blade vibration modes. AD FFT editing was found to be very effective in reducing speckle noise effects in a normal measurement setup using a shaft encoder. It was also demonstrated that similar results are yielded using a 1 PPR tachometer signal for AD transformation. Furthermore it was shown that the cyclostationary characteristic of speckle noise patterns can be exploited in order to yield a synthetic 1 PPR tachometer signal. Since the ADC sampling rate affects the resolution of the resulting rotor speed signal, this approach was found to yield better results in terms of AD FFT editing at higher speeds as the rotor speed could be estimated more accurately. AD low-pass filtering of the synthetic tachometer signal was found to yield some improvement in results at lower rotor speeds.

Further work is envisaged in validating the presented approach on industrial data as well as refining the extraction of a synthetic SNT and extending it to extract a synthetic multiple PPR speckle noise encoder signal.

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