Harmonic Removal als Pre-Processing Schritt für Operational Modal Analysis: Anwendung auf Daten eines betriebenen Getriebes

Harmonic Removal as a Pre-processing Step for Operational Modal Analysis: Application to Operating Gearbox Data

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Kurzfassung

Die Beschleunigungsantwort eines Windgetriebes, das auf einem elektrischen back-to-back Prüfstand der Winergy getestet ist, wird als Eingangsdatensatz für eine pre-processed Operational Modal Analysis (OMA) oder Output-Only Modal Analysis genutzt. Der Datensatz ist erheblich durchsetzt mit diskreten Harmonischen und Seitenbändern der rotierenden Zahnräder, Wellen und Lager. Das verletzt die OMA Annahme ein flaches Spektrum als Input zu haben. Daher werden Methoden im Preprocessing der OMA untersucht, die die Zeitdaten von Harmonischen bereinigen. Die Methoden – Time Synchronous Averaging (TSA), Periodogram basiert und Cepstrum basiert – werden auf Anwendbarkeit auf die Getriebedaten bezüglich Benutzerfreundlichkeit, Ergebnisqualität und Automatisierbarkeit getestet.

Abstract (optional)

The acceleration response of a wind turbine gearbox, tested on a back-to-back test stand of Winergy, is used as input data to a pre-processed operational modal analysis (OMA) or output-only modal analysis. The data is heavily influenced by harmonics and sidebands caused by rotating gear wheels, shafts and bearings. This violates an OMA assumption to have a flat spectrum as input. Therefore, cleaning methods are applied to remove harmonics in the time series. The methods – Time Synchronous Averaging, Periodogram-based and Cepstrum-based – are tested for the applicability to gearbox data concerning their user-friendliness, the quality of the results and possibility of automation.

1. Motivation and Introduction

As the main part of a wind turbine and the drive train, the main gearbox and its vibrational behavior is analyzed by making measurements on a test rig and in the field.

In the system identification of large structures, such as wind turbine gearboxes, the focus is on evaluating which part (e.g. torque arm, housing, etc.) shows which mode form at which frequency. At Winergy, the measured modes are used to validate MBS (multi body simulation) or FE (finite elements) models so that the design can be appropriately modified. Design changes could involve different surface ribbing, modified masses and stiffnesses. It is important to know the modes to improve wind turbine gearboxes in terms of reducing vibration.

As a consequence, modal testing is one part in the chain of testing, model validation and design modifications. Based on the validated models, constructional modification can lead to a reduction of the structure-borne or air-borne noise.

In order to provide an overview of system identification techniques in modal testing, the techniques can be divided into experimental modal analysis (EMA) and OMA.

When instrumenting an EMA, the input force has to be measured simultaneously with the response. The force is generated by a modal hammer or a shaker, and measured using a force transducer. The response is measured using one or several accelerometers. As a result, frequency-response functions are obtained, which describe the acceleration with respect to force.

In the case of excitation using a modal impact hammer, the response could be measured at one or multiple reference points with accelerometers while the hammer points are moving. The alternative is that the grid of accelerometers covers the geometry, and the structure is excited at one location.

When using an electrodynamic shaker, typically one or a few excitation points are instrumented while measuring with a geometrically distributed accelerometer grid.

For the OMA instrumentation, a modal impact hammer or shaker is not necessary; the operating parts represent the excitation of this output-only modal analysis. Hence, one part of the instrumentation is not required, and only accelerometers are used.

One disadvantage of EMA is that heavy equipment is needed to excite such a large structure as a wind turbine gearbox. Furthermore, a comparison between traditional modal testing and OMA indicated that some modes appear or change their properties when the gearbox is operational. The OMA is able to provide modal parameters when the gearbox is driven in correct boundary conditions. Further, some modes are not excited when the gearbox is not operational. Summing up, OMA reveals only the modes of interest that are prominent under normal operational conditions.

One advantage of OMA is that the gearbox being tested is being run under normal operating conditions, and as a consequence, all levels of vibration are comparable with the real situation in the field.

Another advantage is the possibility of using OMA for both test rig and experimental testing in the field when the gearbox is mounted in a turbine.

One of the difficulties of OMA is that automation is not possible with wind gearbox tests today. It needs an experienced user to extract the modes from OMA run-up/run-down experiments. The powerful SSI methods of OMA working in the time domain especially involve a lot of time and resources.

OMA applies several limitations on the excitation of the test object; the most critical one in the gearbox testing scenario is the flatness of the excitation spectra. In the case being considered, the presence of numerous harmonics and sidebands due to three gearbox stages and many rotating elements significantly complicates how it is applied to OMA. The paper presents the approach when dealing with harmonics, and suggests and compares different ways of removing them from the measured signals.

2. Description of the OMA measurement on the test rig

The gearbox being tested is for a wind turbine (the weight is approximately 20 tons without oil). It comprises two planetary stages and one helical stage.

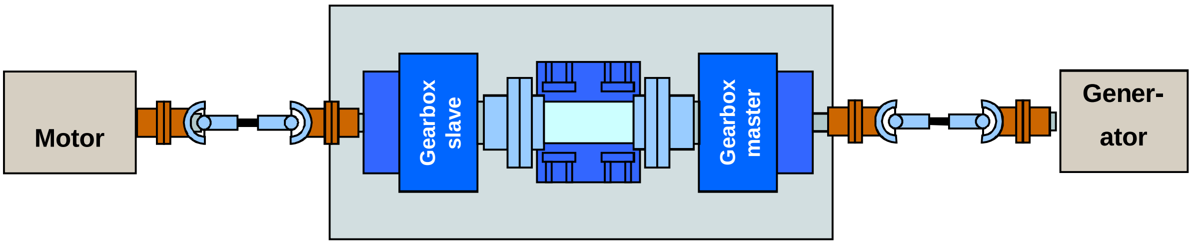


Figure 1: Test rig schematic

The measurements were taken on an electrical back-to-back test rig (see Figure 1). The input is a motor driving the slave gearbox, which is an auxiliary unit to provide the lower speed and high torque to test the master gearbox or test gearbox. The output shaft of the test gearbox drives a generator. The test is performed on a 7.5 MW test rig at Winergy in Voerde.

The gearbox is driven at a constant speed on the test rig at nominal speed and nominal torque.

The housing, torque arm and ring gears of the gearbox are covered with a grid of accelerometers (Bruel & Kjaer, mixed types). There are a total of 70 degrees of freedom

(DOFs). The ring gears of the planetary stages are covered with 26 DOFs and the housing with 44 DOFs (Bruel & Kjaer PULSE Type 7700 is used for data acquisition). Additionally, an optical tacho probe measures the rotational speed of the output shaft.

The planet carriers, planets, wheels, shafts, teeth, bearings and oil splashing generate forces at the corresponding rotational frequencies and its harmonics; these frequencies are being modulated by other rotating parts, creating multiple sidebands. This complex loading excites the entire structure. Since the excitation is heavily dominated by the tonal components, the responses also contain numerous peaks; an example of the response spectrum is shown in Figure 2.

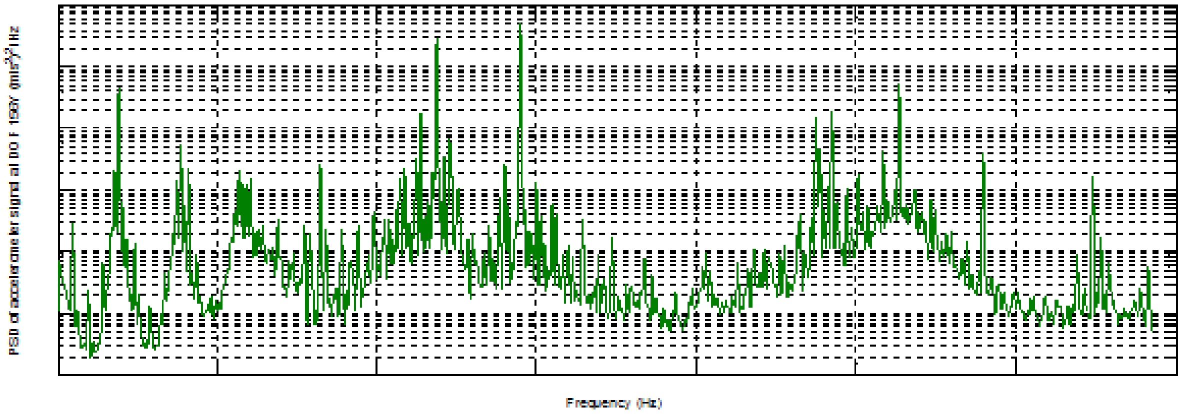


Figure 2: Typical power density spectrum of an acceleration signal measured at a gearbox housing

3. Direct application of OMA to the raw data

When the vibration is dominated by harmonics, directly applying OMA to the measured data typically leads to incorrect results. For example, referred to the most advanced time domain method (OMA SSI), its algorithm automatically selects the complexity of the model to fit the data. Since the harmonics, not the modes, dominate the response, the algorithm selects the model order that best fits the harmonics. In the result, the OMA algorithm confuses the modes with harmonics. This can be clearly identified by very low estimates of the damping ratios of the modes that are identified.

Understanding that OMA's assumption regarding the excitation spectra flatness is violated, one may consider increasing the complexity of the model. Unfortunately, this does not always solve the problem: the uncertainties of the obtained modal parameters are very high. This manifests itself in the very high sensitivity of the modal parameters to the modal extraction settings: a slight change of the settings (e.g. the number of projection channels) leads to significant changes in the identified parameters. This behavior is not physical, and can only be explained by the instability of the algorithm due to the violation of the assumptions the OMA theory is based upon.

4. Techniques for harmonic removal

As one can see, the typical response (as in Figure 2) is the result of some deterministic periodic excitation due to the rotating elements of the gearbox and the broadband stochastic excitation due to multiple random events such as oil splashing, toothing (an impact when two teeth come into contact with one another), rolling in the bearings, etc.

One of the solutions to the problem described in Section 3 would be to separate the response signals at the component due to stochastic excitation and the component due to deterministic excitation. The stochastic component satisfies the OMA assumption and should be kept in the response. The deterministic component does not satisfy the assumption, and should be removed from the response signals. The “cleaned” signal then becomes an input to OMA. The OMA algorithm could deliver much more reliable results if such a separation is possible.

4.1 Time synchronous averaging (TSA)

TSA is a well-known approach to extract a periodic component, corresponding to some phasor, from a signal. A tachometer signal is used to identify the periodic component. The measured acceleration signals are chopped according to the tachometer events, and are averaged together. The resulting (enhanced) signal represents the periodic component, it is defined in one phasor period and repeats itself every phasor revolution. In order to reconstruct the stochastic component, the enhanced signal is replicated along the entire time history and subtracted from the original signal. The result is often called a residual signal. The process is demonstrated in Figure 3.

The advantage of TSA is its simplicity, it does not require any parameters to be set, and not only does it remove the fundamental harmonic, but also the entire harmonic family of the phasor. The drawback is that it requires angular speed stationarity and a good quality tachometer signal. A small (few percent) variation of the angular speed can be compensated by converting the signal to angular domain, followed by signal enhancement in this domain (angular synchronous averaging, ASA). It is more difficult to deal with a tachometer signal that is not perfect (tachometer jitter). In this case, the harmonics are not completely removed from the signal, and their traces can still be seen in the spectra.

If several phasors are present in the system, the signal enhancement is repeated for each phasor. In this case, it is important to know the exact gear ratio (i.e. the expression involving integer numbers representing all gears separating the shafts). Not knowing the exact gear ratio may cause significant deviation at the end of the time history, and can completely destroy the averaging.

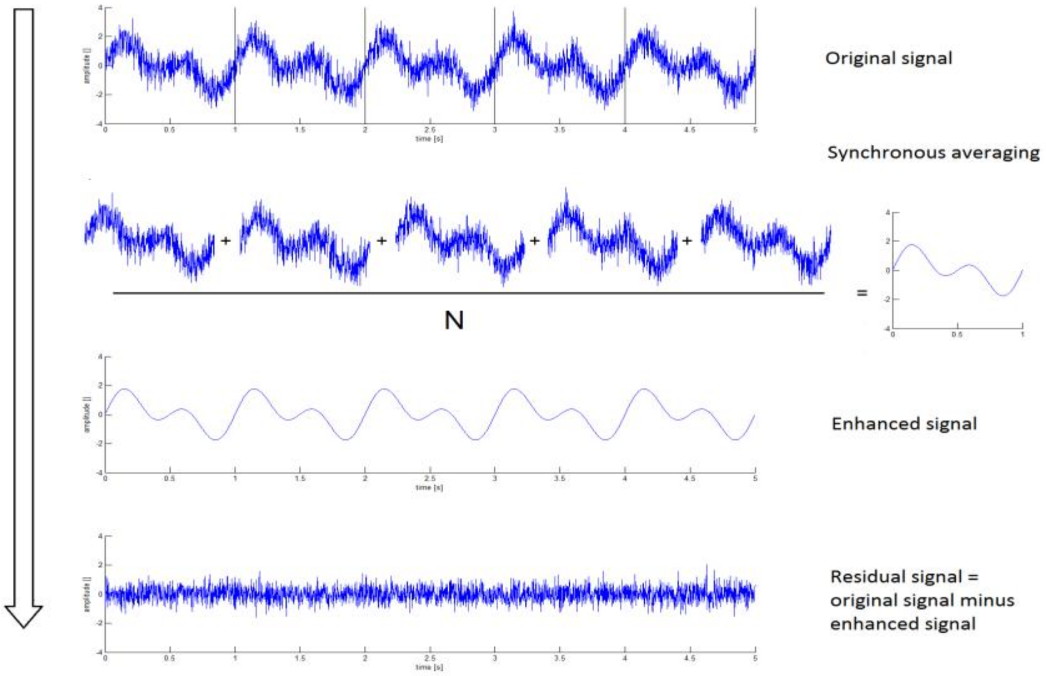


Figure 3. Time Synchronous Averaging procedure

The result of applying the TSA/ASA algorithm to one of the gearbox signals is shown in Figure 4. In this particular case the TSA algorithm was applied 5 times.

Unfortunately, for the case of complex gearbox testing, the TSA/ASA method is inconvenient: there are simply too many phasors in the system; each needs to be identified – and its exact gear ratio must be calculated. This is a very tedious and time consuming task, and calls for different method(s) which does/do not require the identification of the harmonics. These methods are considered in the following sections.

4.2 Methods that do not require exact knowledge of the phasors

4.2.1 Cepstrum

Utilization of cepstrum for removing harmonics from a time signal was originally suggested in [1]. Cepstrum is defined as the inverse Fourier transform of the log spectrum of the signal [2].

$$C(\tau) = \mathfrak{F}^{-1}\left[log\left(X(f)\right)\right],$$

where $X(f) = \mathfrak{F}[x(t)]$ is the Fourier transform spectrum of signal $x(t)$.

Treating the logarithm of the spectrum as a waveform and applying Fourier transformation, underlines periodicities in the spectrum, and allows them to be detected and removed. The term *cepstrum* is derived by swapping the order of the letters in the word spectrum. Similarly, the name of the independent variable of the cepstrum is known as a *quefrency*, and the linear filtering operation is known as *liftering* [2]. Cepstrum operator $C(\tau)$ is reversible, i.e. it allows a return to be made back to the time domain after cepstrum editing, This can be done by combining the edited spectrum amplitudes with the original phase spectrum. The procedure is illustrated in Figure 5. and detailed in [1].

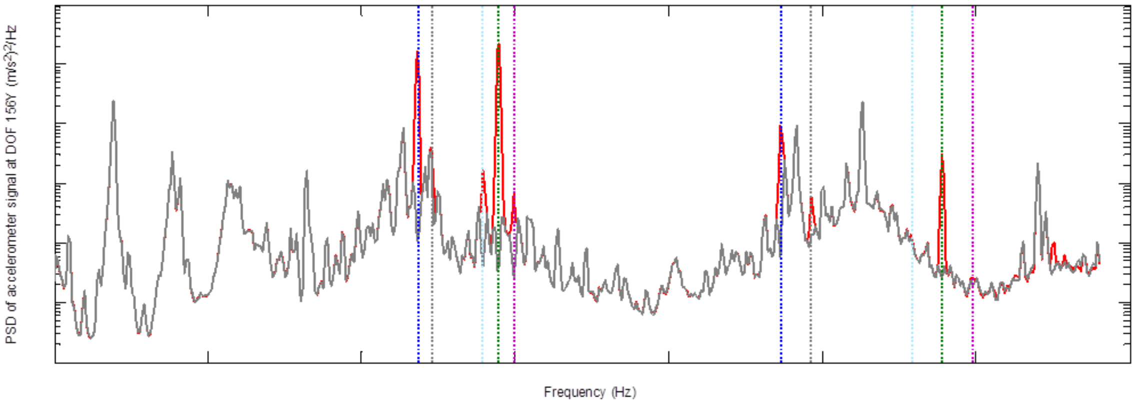


Figure 4. Spectra of the raw signal (red) overlaid with the spectra after applying TSA; The vertical dotted lines denote the harmonics that were removed

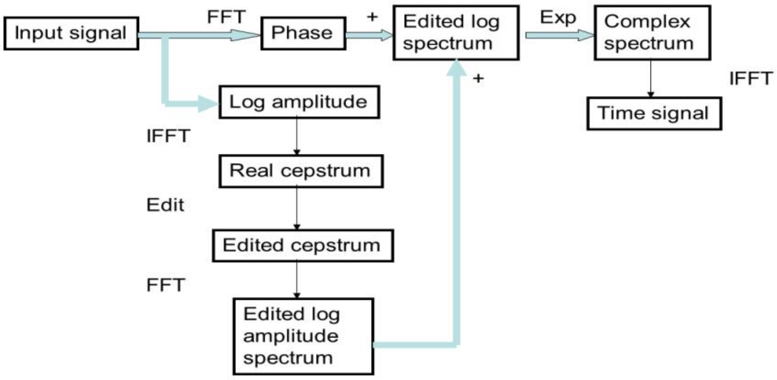


Figure 5. Cepstral procedure

Cepstrum concentrates any periodic components of the spectra, such as families of equally spaced harmonics and sidebands, into a small number of peaks called “rahmonics”. An editing procedure is then applied to detect and remove rahmonics. Different editing techniques can be suggested. For example, a comb lifter [1] will remove a family of harmonics at once, but it requires the knowledge of harmonics of interest, and is not convenient for a gearbox.

Another example of the editing procedure is a low-pass or exponential lifter [1]. In this case, no preliminary knowledge about harmonics is required, and *all* harmonics are removed, which makes this approach most convenient when analyzing gearboxes. This method is based on the assumption that modal properties are concentrated at low quefrencies of the cepstrum. Both low-pass and exponential lifters keep the values of the cepstrum at low quefrencies, and remove or attenuate the higher quefrencies. Both lifters have a smoothing effect on the spectrum. Consequently, the crucial point is to find a suitable value of the lifter parameters to remove/attenuate unwanted harmonics, while keeping the modal behavior in the frequency spectra.

4.2.2 Periodogram

The method uses the auto-periodogram P_{xx} to locate and remove the harmonics. The method was introduced in [3].

The idea of the method is to perform a discrete Fourier transform (DFT) of the entire signal, detect and remove the peaks corresponding to the harmonics, and, using inverse Fourier transform, convert the signal back to the time domain.

The obtained Fourier spectrum is complex, with the number of lines equal to the number of samples in the original signal:

$$X(k) = \sum_{n=1}^{N} x(n) e^{j2\pi k\frac{n}{N}}.$$

The auto-periodogram is obtained as a product of the DFT of the signal with itself, scaled by the squared number of samples:

$$P_{xx} = \frac{1}{N^2} X(k) \cdot X^*(k).$$

As the peaks due to harmonics are sharp, and the peaks due to modal behavior are smooth, a smoothing procedure is subsequently applied. This removes/attenuates the former, and leaves the latter unaffected. In the last step, the smoothed periodogram is transformed back to the time domain.

The suggested smoothing technique uses a moving median of the signal periodogram as a threshold for detecting harmonics. The detected picked peaks are removed by replacing them by the values at the median. The original and resulting spectra are shown in Figure 6.

In the case of slight RPM variation, it might be beneficial to resample the original signal in the angular domain. The resulting periodogram will have an order axis instead of a frequency axis. The peaks due to harmonics, possibly smeared due to the RPM variation in the frequency domain periodogram, will stay sharp in order domain periodogram.

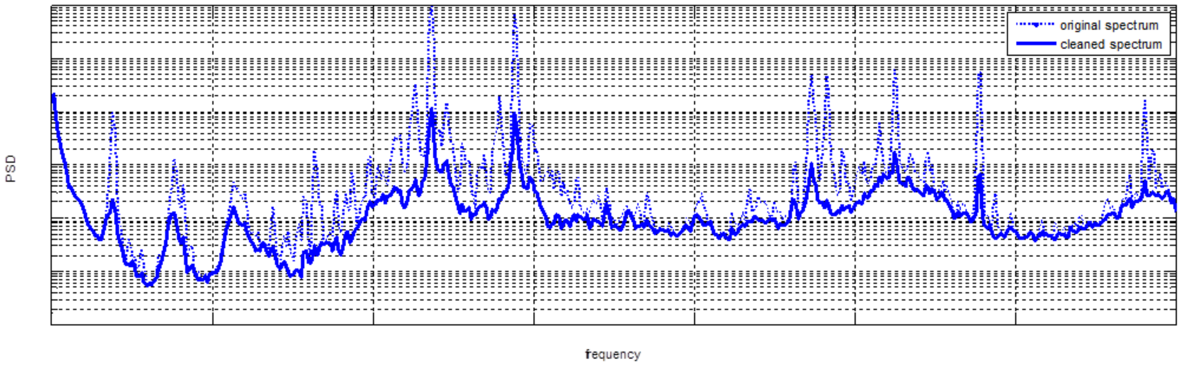


Figure 6. The spectra of original (dotted line) and the signal after application of the peridogram-based method

5. Application to OMA, results, discussion

This section presents the results of OMA performed on the data pre-processed by the periodogram method presented above. The time histories resulting from the method were exported to OMA software (Bruel and Kjaer Type 7760), where the SSI UPC was employed. For demonstration purposes, we focus on a narrow frequency range that contains both harmonics and few important low frequency modes. The fragment of the stabilization diagram is shown in Figure 7.

The algorithm finds three modes around the left peak (modes I…III) and three modes around the right one (modes IV…VI). Let us first consider modes I…III. These modes are quite distinct (the MAC values between them are shown in Table 1.)

Comparing the animation of the mode shapes, we can conclude that mode I is dominated by rolling (rotation around the vertical axis) and also contains an axial clockwise (CW) torsional component. Mode II is mainly a torsional mode with counter-clockwise (CCW) rotation, and mode III is dominated by rocking motion, i.e. rotation around the axis connecting the torque arms.

“Rotation” or “whirling” of mode shapes is quite typical for common structures without moving parts. For these structures, most of the nodes either move in phase or in anti-phase. However, in structures with rotating elements, rotation of mode shapes is quite common. It is distinguished between forward and backward whirling modes. The whirling direction is defined by the sign of the phase angle between the displacement vectors (Figure 8).

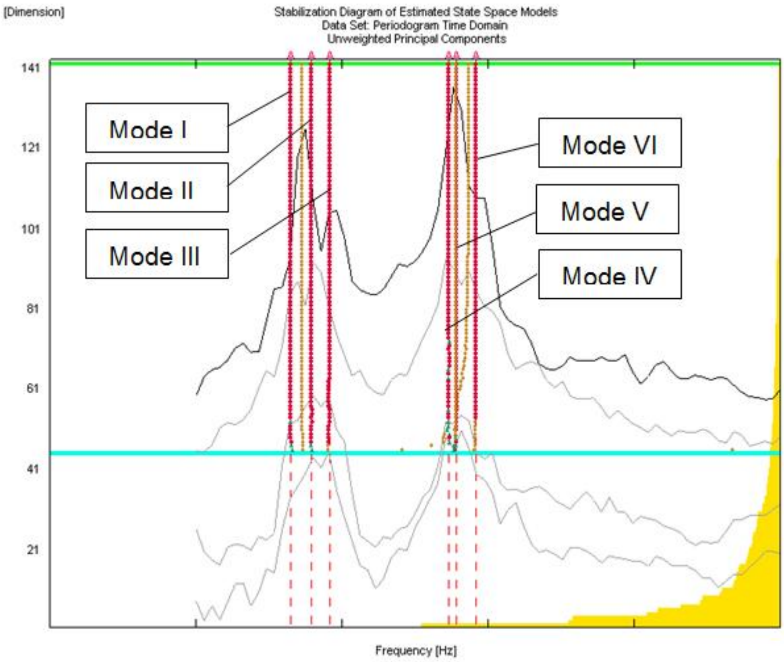
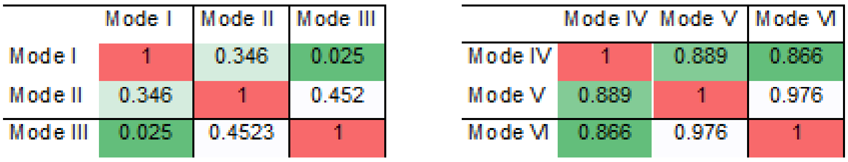


Figure 7. Fragment of the stabilization diagram



	Mode I	Mode II	Mode III
Mode I	1	0.346	0.025
Mode II	0.346	1	0.452
Mode III	0.025	0.4523	1

	Mode IV	Mode V	Mode VI
Mode IV	1	0.889	0.866
Mode V	0.889	1	0.976
Mode VI	0.866	0.976	1

Table 1. Fragments of the MAC table for the modes in Figure 7

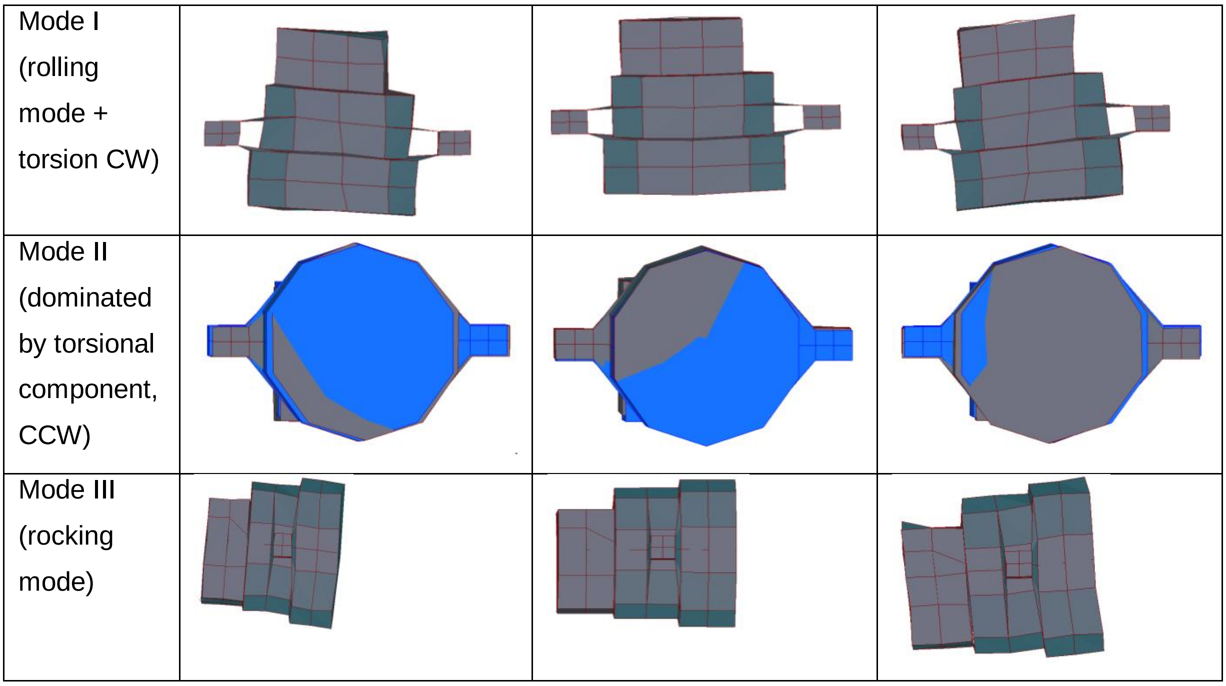


Figure 8. Whirling motion of the modes

The modes around the right peak in Figure 7 are not that well defined, and their MAC values are high (Table 1). However, when the mode shape animation is observed, the different whirling direction for modes IV and VI can be identified. Figure 9 shows the step-wise animation of these two modes, with CW and CCW whirling directions.

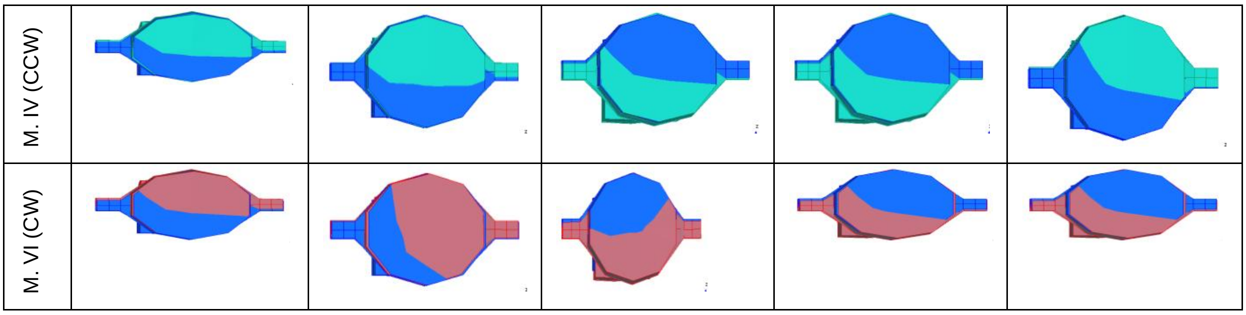


Figure 9. Different whirling rotations of mode shapes for modes IV and VI.

6. Conclusion

A modal test and analysis in operation can show additional or shifted modes. In order to improve the applicability of OMA to wind turbine gearbox data, the measured data will be pre-processed to remove harmonics and sidebands.

The measured response of the tested gearbox consists of many rotating parts, and it is heavily dominated by numerous harmonics due to shafts, gears, their harmonics and sidebands. Vibration of one stage is modulated by the rotating elements of other stages, which creates even more harmonics in the response.

This makes it difficult to apply OMA to the data, since one of the OMA assumptions regarding the flatness of the input spectra is violated.

In order to clean up the measured response data, three techniques, namely, TSA/ASA, a Cepstrum-based method and periodogram-based method have been applied.

TSA/ASA, which typically performs well, has proven to be useless in this case due to the huge amount of harmonics, each of which has to be identified and consequently removed. Cepstrum-based cleaning works well where families of harmonics are well defined, which is not the case for most of the harmonics here. The method will not work for sidebands, which are also present in the response. The Periodogram method indicated that it can be used, but it is still not straightforward to apply this method. Selecting different smoothing parameters will obviously affect damping. Therefore, the smoothing parameters have to be adjusted carefully.

The results presented in Section 5 not only reproduce the dynamics known previously, but also reveal additional information.

The last technique indicates very good results and improves the quality of the modal analysis. The results of the OMA more clearly separate the various modes from one another. For example, a previously known mixed rocking and lateral tilting mode is separated here in the single mode forms. The exact separation simplifies the validation of numerically identified solutions such as MBS (multi-body simulation) models.

In the current state, the harmonic removal pre-processing cannot substitute user experience, and for the time being, this technique still cannot be automated. Nevertheless, the manual intervention by the user is less time-consuming. Further development of the methodology is required to respond to the challenges discussed in the introduction.

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