

# Chapter 10

## Experimental Characterization of Wind Turbine Gearbox in Operation

**Emilio Di Lorenzo and Simone Manzato**

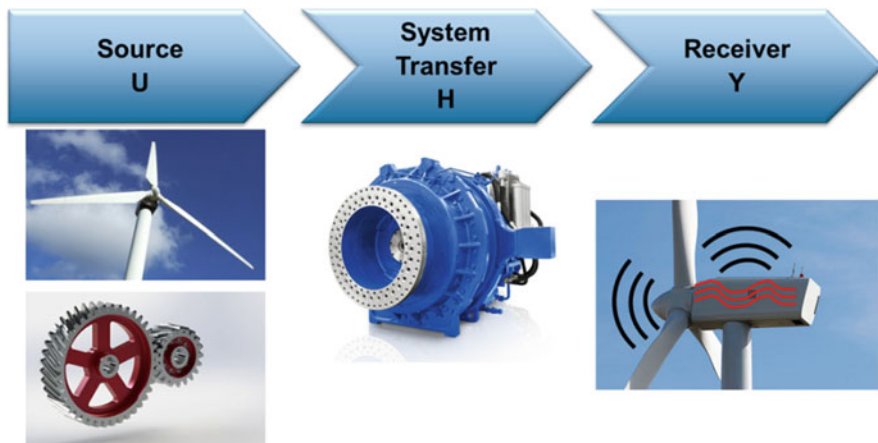
**Abstract** The gearbox is one of the key subsystems in a geared wind turbine, as it must transfer the power from the low speed shaft connected to the rotor to the high speed shaft connected to the generator. As turbines become larger, more power can be generated, but consequently gearboxes with higher load capacity need to be designed. Gaining a deep knowledge into gearbox dynamics becomes of fundamental importance and more and more accurate and detailed noise and vibration measurements are demanded. When dealing with a machine in operating conditions with several rotating components and, in particular with a multi-stage transmission system, components are introduced in the signal that make the application of standard techniques such as Operational Modal Analysis (OMA) very difficult and in some cases almost impossible. For this reason, new techniques to tackle with these conditions have been investigated, such as Order Based Modal Analysis (OBMA). As suggested by its own name, this technique is a combination of Order Tracking and Operational Modal Analysis. On one hand, OMA is based upon the calculation of auto- and cross-powers and it works very well for most cases. On the other hand, OBMA is based upon the extracted orders during run-up or coast-down. During such events, the orders are sweeping through a certain frequency band which is useful for characterizing the dynamic behavior of the rotating structures.

### 10.1 Introduction and Motivation

The current approach in industry is to qualitatively measure the vibrations generated by the dominant excitation sources as well as the overall sound power levels, so that the machine performance can be certified according to standards and/or customer specifications. However, as mentioned, by following this approach only qualitative information can be obtained and the root causes of high vibration levels or acoustic tonalities cannot be understood. Also, analyzing these data requires a lot of user-interaction, as each peak need to be independently analyzed. Experimental modal analysis techniques (Heylen et al. 2013) aim at identifying a system characteristic

---

E. Di Lorenzo (✉) • S. Manzato  
Siemens Industry Software (SISW), Interleuvenlaan 68, 3001 Leuven, Belgium  
e-mail: [emilio.dilorenzo@siemens.com](mailto:emilio.dilorenzo@siemens.com); [simone.manzato@siemens.com](mailto:simone.manzato@siemens.com)



**Fig. 10.1** The Source-Transfer-Receiver approach applied to a wind turbine gearbox

model based on input/output dynamic measurements. By identifying the origin of each of the phenomena of interest, it is possible to understand where corrective action should be applied increase the system NVH performances. Additionally, the identification of a system characteristic model will allow designer to compare experimental and numerical models using similar quantities. This approach will objectively quantify the agreement between the design assumptions and the behavior of the real structure.

The method is based on the so-called Source-Transfer-Receiver approach, as shown in Fig. 10.1 for a wind turbine gearbox. Experimental Modal Analysis relies on measurements of the system response at the receiver (i.e. acceleration) due to the measured inputs at the sources (typically forces) to identify a System Transfer function which represent the dynamics of the system itself. Modal Analysis will try to represent the information in the measured system transfer as natural frequencies, damping ratios and mode shapes. During operations, however, measuring the forces into the system can be practically impossible (for a gearbox, these are the loads transmitted from the whole turbine via the main shaft and the gearbox supports as well as the internal gear contact forces). Methods have been developed to overcome this limitation and thus allow to identify the modal properties of a system also in operating conditions, provided some assumption on the forces acting on the systems are verified (Peeters et al. 2007; Carne and James 2010). However, the main forces acting on a gearbox during operations appear at discrete frequencies multiple of the fundamental rotational speed. As one of the assumptions of Operational Modal Analysis is on the broadband spectrum of the forces, it is clear that identifying a modal model during stationary conditions is practically unfeasible for a gearbox, where the harmonic density is such that barely any mode is visible (Manzato et al. 2013).

However, during transient operations such as run ups and run downs, the rotational speed, and consequently its harmonics, is varying during the measurement. The different orders are then sweeping in a frequency band which is related to the minimum and maximum rotational speeds. As it happens during a sine sweep test, whenever one of these orders crosses a resonance, the response will increase accordingly. Orders can then be considered as representative of the system transfer (Fig. 10.1) and modal parameters identification techniques can be applied. The method was first introduced few years ago as Order based Modal Analysis (Janssens et al. 2006) and was further developed and validated recently. In this section, the concept of the method will be reviewed, with particular focus on the techniques required to extract orders that can be successfully used for modal analysis. Moreover, it will be positioned against standard Operational Modal Analysis techniques, showing the clear advantages in identifying reliable modal models of operating rotating machines and in particular for the wind turbine gearbox case.

As already discussed, the identification of operational modal model will allow not only to characterize the dynamic response of a structure in operating conditions, but will also provide means of validating, and subsequently updating, global numerical models developed with Multi Body and Finite Element tools, as demonstrated in Goris et al. (2013).

## 10.2 Order Tracking Techniques

Order tracking is the analysis of frequency components whose frequency is related to the rotational frequency of the operating machine. If the machine is running in non-stationary conditions, then the frequency components will be time varying and some more information are needed in order to perform the analysis. The additional information are in the form of tachometer signals measured on reference shafts of the machine. Several methods have been employed to digitally track orders which results from rotating components in noise and vibration problems (Blough 1998). In order to allow the computation of the exact frequency for the orders of interest, an accurate tachometer signal is needed for all the methods discussed in this section:

- Time domain sampling Fast Fourier Transform (FFT) order tracking;
- Angle domain computed order tracking;
- Time Variant Discrete Fourier Transform (TVDFFT);
- Vold-Kalman (VK) filter based order tracking.

### 10.2.1 Time Domain Sampling-Based Fast Fourier Transform Order Tracking

The simplest digital order tracking techniques are based on the FFT on time domain data. These methods require time domain data sampled with a constant  $\Delta t$  (Fig. 10.2). The method performs a sliding FFT on time domain data and calculates the average rpm over which the transform is performed. This averaged rpm is then used for estimating the frequency of the orders of interest for each estimated spectra. Finally, the amplitude and the phase of the order are extracted from the FFT spectra. The order itself will not always fall on a single spectral line, so normally multiple spectral lines are summed. The FFT kernels are given in Eqs. (10.1) and (10.2), where  $x(n\Delta t)$  is the  $n$ th discrete data sample,  $f_m$  is the frequency of the sine/cosine terms and  $a_m$  and  $b_m$  are the estimated Fourier coefficients:

$$a_m = \frac{1}{N} \sum_{n=1}^N x(n\Delta t) \cos(2\pi f_m n\Delta t) \quad (10.1)$$

$$b_m = \frac{1}{N} \sum_{n=1}^N x(n\Delta t) \sin(2\pi f_m n\Delta t) \quad (10.2)$$

The main advantage of this method is its computational efficiency. However, an important limitation is the constant time over which the transform is performed, regardless of the rpm of the machine. Additionally, it is assumed that all the sinusoidal functions are constant in amplitude over the time that the transform is performed. A leakage error is also present as orders are estimated by using an FFT based approach and a Hanning window is typically applied in order to reduce this effect.

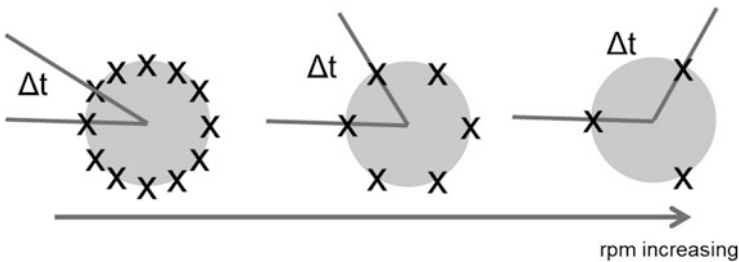


Fig. 10.2 Time domain sampling based FFT order tracking representation

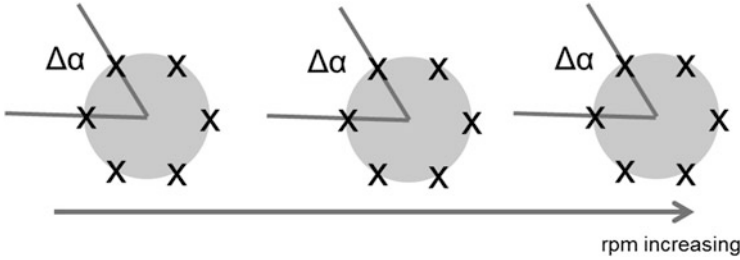


Fig. 10.3 Angle domain order tracking representation

### 10.2.2 Angle Domain Resampling Order Tracking

A very well-known order tracking method which is widely used in commercial software is based on angular resampling. Data are acquired with a uniform  $\Delta t$  and then resampled to the angle domain through the use of an adaptive digital resampling algorithm. The final result of the technique is that uniform  $\Delta t$  data become uniformly spaced angle data (Fig. 10.3). Estimates of amplitude and phase of the orders are obtained by processing these data with a Discrete Fourier Transform (DFT) instead of a FFT for computational flexibility in performing the transform without being restricted to a power of two number of samples.

In order to perform the transformation from time domain data to angle domain data, a reference signal has to be selected to define the instant of time in which the uniform angular intervals have been spaced. Typically, this signal is considered to be the tachometer signal measured on a reference shaft of the operating machine. The kernels of the Fourier transform are reformulated as shown in Eqs. (10.3) and (10.4), where  $o_m$  is the order which is being analyzed:

$$a_m = \frac{1}{N} \sum_{n=1}^N x(n\Delta\theta) \cos(2\pi o_m n\Delta\theta) \quad (10.3)$$

$$b_m = \frac{1}{N} \sum_{n=1}^N x(n\Delta\theta) \sin(2\pi o_m n\Delta\theta) \quad (10.4)$$

The advantages of the resampling based order tracking are leakage free estimates of orders which fall on spectral lines as well as an order resolution which is constant in terms of width. On the other hand, also this method has several restrictions. Orders may only be tracked with reference to one rotating shaft and it is very difficult to distinguish among order which cross one another. Another limitation is due to the finite defined order resolution which makes very difficult the analysis of orders which do not fall on a spectral line.

### 10.2.3 Time Varying Discrete Fourier Transform (TVDFFT)

The Time Variant Discrete Fourier Transform (TVDFFT) method gives results very similar to the resampling based order tracking, but with less computational efforts. It is based on a Fourier transform kernel whose frequency varies with time and it does not require the transformation from the time to the angle domain (Blough et al. 1997). The TVDFFT is based on kernels in which the sine and cosine functions have unity amplitude and an instantaneous frequency matching that of the tracked order at each instant in time, as shown in Eqs. (10.5) and (10.6):

$$a_m = \frac{1}{N} \sum_{n=1}^N x(n\Delta\theta) \cos \left( 2\pi \int_0^{n\Delta t} (o_m * \Delta t * rpm/60) dt \right) \quad (10.5)$$

$$b_m = \frac{1}{N} \sum_{n=1}^N x(n\Delta\theta) \sin \left( 2\pi \int_0^{n\Delta t} (o_m * \Delta t * rpm/60) dt \right) \quad (10.6)$$

The formulation can be extended in order to separate close or crossing orders through a secondary calculation. There can be a leakage error using the TVDFFT with constant  $\Delta t$  sampled data because it is not guaranteed that the integer revolution values required for a constant order bandwidth analysis will fall on a  $\Delta t$ . If it is not the case, it will lead to a leakage error by performing the transformation over a non-integer number of revolutions. This error can be reduced by oversampling the data to finer  $\Delta t$ . The method retains most of the advantages of the resampling based order tracking and it can be implemented in a very efficient manner without having the computational load and complexity of the transformation from the time domain to the angle domain.

### 10.2.4 Vold-Kalman (VK) Filter-Based Order Tracking

Vold and Leuridan (1993) introduced an algorithm for high resolution, slew rate independent order tracking based on the concepts of Kalman filtering. The Vold-Kalman (VK) algorithm allows tracking multiple orders at the same time and it is able to decouple close and crossing orders. This method extracts the time history of the order as well as the estimate of the amplitude and the phase of the same order.

As the Kalman filter is based on the process and measurement equations, the VK filter is based on the structural and data equations. The structural equation describes the mathematical characteristics of the order to be extracted. It relies on information from the tachometer signal and represents a sine wave whose frequency and amplitude are constant over three consecutive points. To account for deviations

from a perfect sine wave over the considered time samples, a non-homogeneity term  $\varepsilon(n)$  is introduced on the right-hand side of Eq. (10.7):

$$x(n) - 2 \cos(\omega\Delta t)x(n-1) + x(n-2) = \varepsilon(n) \quad (10.7)$$

where  $x(n)$  represents the  $n$ th discrete time sample and  $\omega$  the instantaneous frequency of the sine wave. The second equation of the VK method is the so called data Eq. (10.8) and describes the relationship between the order  $x(n)$  and the measured data  $y(n)$ . Normally the measured data are a combination of all orders generated in the machine plus a random noise component. This random noise, as well as the non-tracked orders, are then combined into the signal  $\eta(n)$ :

$$y(n) = x(n) + \eta(n) \quad (10.8)$$

A weighted solution is obtained by introducing the Harmonic Confidence Factor (HCF)  $r$ . This value determines the tracking characteristic of the filter and is calculated according to Eq. (10.9) as the ration between the standard deviations of the structure and data equations:

$$r(n) = \frac{s_\varepsilon(n)}{s_\eta(n)} \quad (10.9)$$

Choosing large values of  $r$  leads to a highly selective filtering in the frequency domain; on the contrary, small values will decrease the frequency resolution while obtaining faster convergence. By applying the ratio as a weighting function and combining the two previous equations, the system in Eq. (10.10) is obtained:

$$\begin{bmatrix} 1 & -2 \cos(\omega\Delta t) & 1 \\ 0 & 0 & r(n) \end{bmatrix} \begin{bmatrix} x(n-2) \\ x(n-1) \\ x(n) \end{bmatrix} = \begin{bmatrix} \varepsilon(n) \\ r(n)y(n) - \eta(n) \end{bmatrix} \quad (10.10)$$

Applying Eq. (10.10) to all observed time samples will give a global system of over-determined equations for the desired waveform  $x(n)$  that can be easily solved with standard least square techniques. For the specific case of order tracking, the filtered waveform is most conveniently described in terms of amplitude and phase with respect to a reference channel such as the tachometer.

### 10.3 Order-Based Modal Analysis

Operational Modal Analysis (OMA) algorithms, such as Operational Polymax (Peeters et al. 2007), allow the identification of the modal parameters of a structure by taking into account only operational measurements. However, when applied to data acquired during transient phenomena, such as run ups and coast down, data

need to be carefully interpreted. Input data for the modal parameter identification process are auto and cross spectra calculated from the complete time histories and assuming the excitation can be considered broad-band white noise. However, when spectra are calculated on run up data of rotating machineries, sharp peaks appears at fixed intervals. These peaks relate to the so-called “end-of-order” effect and originate from order components suddenly stopping at the maximum rpm. When using this spectra in standard OMA, they will be erroneously identified as physical poles from the algorithm; additional, they can hamper the accuracy in the estimation of modes at nearby frequencies.

The idea of performing OMA on tracked orders instead of considering the spectra arose because, during a run-up or run-down test, the measured response are mainly caused by the rotational excitation. In this formulation, the run-up or run-down is then considered as a multi-sine sweep excitation in the frequency band of interest. The excitation force acting on the structure is considered to be equivalent to that of a rotating mass with increasing (or decreasing) frequency, which can be represented as two correlated perpendicular forces of equal amplitude and in quadrature (90° phase difference). The measured structural response can then be represented in the frequency domain as shown in Eq. (10.11) where the terms  $F$  relate to the forces while the  $H$  indicate the corresponding columns in the transfer function matrix:

$$Y(\omega) = H_{(:,fx)}(\omega) F_x(\omega) + H_{(:,fy)}(\omega) F_y(\omega) \quad (10.11)$$

Taking into account the relation between the two perpendicular rotating forces and considering only the positive frequency axis, Eq. (10.12) is obtained:

$$Y(\omega) \propto \omega_0^2 \left( H_{(:,fx)}(\omega) - jH_{(:,fy)}(\omega) \right) \delta(\omega - \omega_0) \quad (10.12)$$

where  $\omega_0$  is the rotation speed. This equation shows that the measured output is proportional to the squared rotation speed and to a complex combination of two structural FRFs related to  $x$  and  $y$  excitation. In general, a structural FRF can be modally decomposed as shown in Eq. (10.13):

$$H_{(:,\bullet)}(\omega) = V(j\omega I - \Lambda)^{-1} L_{\bullet} + \frac{1}{\omega^2} LR_{\bullet} + UR_{\bullet} \quad (10.13)$$

where  $LR$  and  $UR$  are the real-valued lower and upper residuals which are used for modeling the influences of the modes outside of the considered frequency band.  $V$ ,  $\Lambda$  and  $L$  are the mode shape matrix, the diagonal matrix containing the complex poles and the modal participation factors. Equations (10.11) and (10.13) show that modal analysis can be applied to displacement orders taking into account that:

- Displacement orders are proportional to the squared rotation speed and, as a consequence, acceleration orders are proportional to the forth power of the same rotation speed. The main difference is that in the classical modal analysis the acceleration FRFs are proportional to the squared frequency axis.



- Upper and lower residuals are complex, while in classical modal analysis they are real.
- Participation factors are complex both in classical and order based modal analysis.

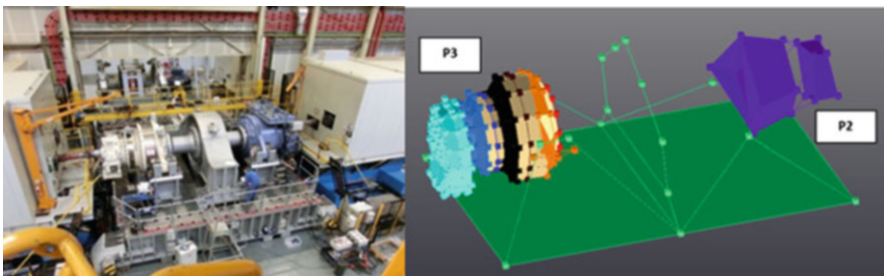
Methods such as Operational Polymax and Operational Polymax Plus are robust against these observations and they can be employed for estimating the modal parameters in case of rotating machineries by looking at the orders rather than at the spectra.

## 10.4 Dynamic Characterization of Operational Gearboxes

With the main objectives of characterizing the gearbox dynamic response in different operating conditions and obtaining experimental data for model validation and updating, a measurement campaign took place on the 13.2 MW dynamic test rig at ZF Wind Power in Lommel, Belgium (Fig. 10.4). Using this test rig, gearboxes can be tested under representative loading condition using parameterized load cases that can be programmed into the test rig controller. In this case, the following scenarios were tested:

- Shaker sine sweep during standstill and in stationary operating conditions at 1200 rpms.
- Stationary operating conditions at 1200 and 800 rpms.
- Run up from 200 to 1500 rpms with a speed of 5 rpms/s.
- The operational measurements were all repeated under different torque loading (33 %, 66 % and 100 % of nominal torque).

As shown in Fig. 10.4 (right) an extensive grid of 250 points on both the gearboxes and the test rig was measured using tri-axial accelerometers. To measure all points, the whole test schedule was repeated 7 times roving the available sensors to cover the whole grid. To ensure the data form the different dataset could be



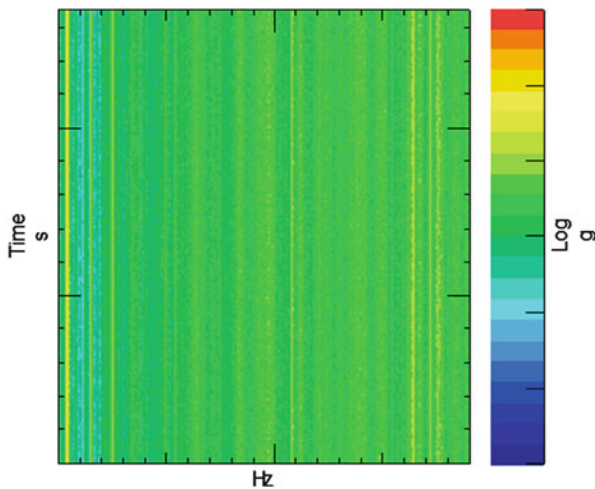
**Fig. 10.4** Test-rig configuration (*left*); markers identifying the measurement points on the test-rig (*right*)

compared, a set of 7 single axis accelerometers was always kept in the same positions. 3 optical sensors (zebra tape + laser) were respectively installed on the Low Speed Shaft and at the High Speed Shaft of each of the two gearboxes in the test rig.

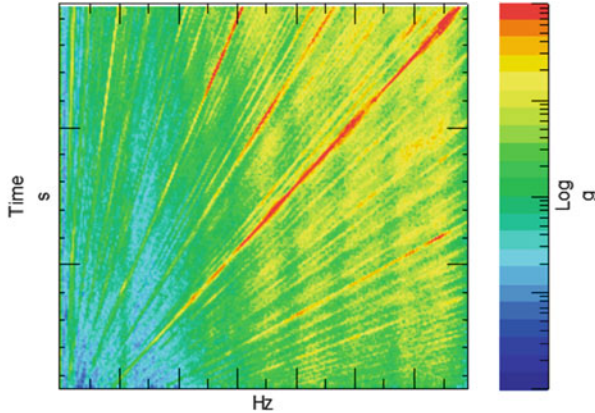
With the objective of comparing the modal parameters obtained in different operating conditions, data measured during shaker excitation with the gearbox in standstill conditions have been analysed. After computing Frequency Response Functions, standard Experimental Modal Analysis methods were applied and a set of reference modal parameters obtained (Manzato et al. 2015). A similar processing was also performed on the data collected applying the sine sweep via the shaker during stationary operations. However, although some of the modes could still be identified, it was concluded that the shaker were not powerful enough to sufficiently excite the structure and ensure a reliable modal estimation.

Response data acquired during acceleration measurement were also acquired and the signature of the gearbox during operation at constant speed is shown in Fig. 10.5.

All vertical lines in the time-frequency diagram represent highly excited harmonics of the fundamental rotational speed and they can all be related to rotational speed of the shafts of the different stages as well as to the gear meshing frequencies. As the response is dominated by narrow and closely spaced harmonic components, standard Operational Modal Analysis cannot be applied. As a consequence, to understand the response, only Operational Deflection Shapes can be analysed, but, as mentioned, it will be impossible to understand whether the high response at the receiver is due to the system or the source (Fig. 10.1). Of course one could compare the harmonic frequency with the natural frequencies identified by applying shaker excitation in stationary conditions. However, as the boundary conditions



**Fig. 10.5** Signature of the gearbox on the test rig during stationary operations



**Fig. 10.6** Signature of the gearbox on the test rig during a run-up at 5 rpm/s

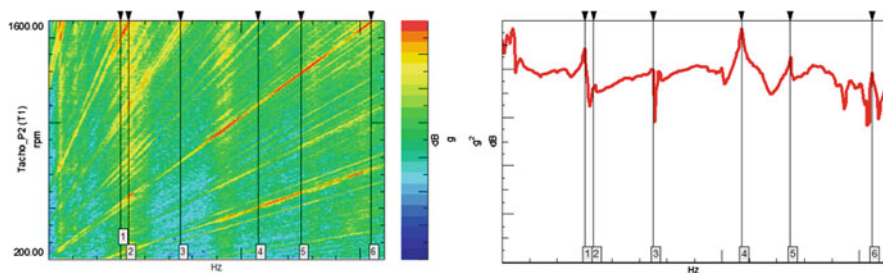
between standstill and operational conditions are significantly different, erroneous conclusion might be derived.

The signature obtained during a run up is significantly different and is shown in Fig. 10.6. In this case, the different orders vary in frequency and the resulting excitation is similar to that of a multi-sine sweep. As will be explained in the next sections, both Operational and Order-based Modal Analysis can be applied to these data to extract the modal parameters.

#### 10.4.1 *Operational Modal Analysis*

Operational Modal Analysis requires as input data acceleration auto and cross-spectra calculated using the complete time history. The results can then be considered as an average over time of the frequency response shown in Fig. 10.5. By combining the response at the different orders, the resulting spectra can be considered as the response to a “flat” broadband excitation, thus complying with the OMA assumption. The resulting spectra are shown in Fig. 10.7. Although the spectrum shown is suitable for OMA processing, the results might be wrongly interpreted if the data are not carefully analysed.

A comparison of the two graphs reveals that some of the peaks in the spectrum (and in particular the sharpest ones) originate from order components suddenly stopping at the maximum rpms. Cursors were added to the pictures at frequencies that were identified as poles of the gearbox by classical OMA. Moreover, as the two gearboxes on the test rig were slightly different prototypes, they rotate at slightly different speeds, resulting on a doubling of these “end-of-order” related poles. This is the main weakness of this method: not only the real poles are identified, but also the so-called “end-of-order” related poles which are physically not present



**Fig. 10.7** RPM-frequency spectrogram of the gearbox run up and corresponding spectrum

in the system and are purely processing artifact. The four identified frequencies correspond to some of the main order components ending at that frequency. The estimated modal model is consequently not correct because it considers them as poles of the system. While these poles could be ignored a-posteriori, in cases where many orders are present (such as this one) they can also affect the estimation of close modes, thus reducing the confidence in the identified model.

### 10.4.2 Order-Based Modal Analysis

The conclusions from Sect. 10.4.1 motivated the development of a new method able to reliably identify a modal model of a rotating machine during operation. Instead of applying modal parameter identification on the spectra, the concept is to identify the dominant orders in the response and then use them to extract the modal parameters in the frequency band of interest. The process to perform Order-based Modal Analysis is displayed in Fig. 10.8. The first two steps pre-process the tacho data to remove spikes that could be present in the signal and make it smoother. Once the tacho is corrected, order tracking can be applied using one of the techniques discussed in Sect. 10.2 and the orders of interest extracted. On each of these orders operational modal identification can then be applied and the modal parameters from the different orders combined to obtain the modal response in the frequency band of interest.

As an example, Fig. 10.9 compares the cross-power spectrum and the 1st order of the high speed gear stage order (1st gear mesh frequency of the High Speed Stage) for the same channel over the same frequency bandwidth. The order is estimated using two of the techniques presented in Sect. 10.2, namely the Time varying Discrete Fourier Transform (TVDFFT) and the Vold-Kalman filter (VK). It can be observed that, while the cross spectrum on the left spans the complete frequency band, the order only starts from a higher minimum frequency. To span the full bandwidth, different orders need to be extracted and the modes identified.

Applying the classical OMA processing (see Sect. 10.4.1) and using the Operational Polymax algorithm, 13 modes are identified in the frequency band between 80 and 400 Hz. The same processing was repeated for different load levels to

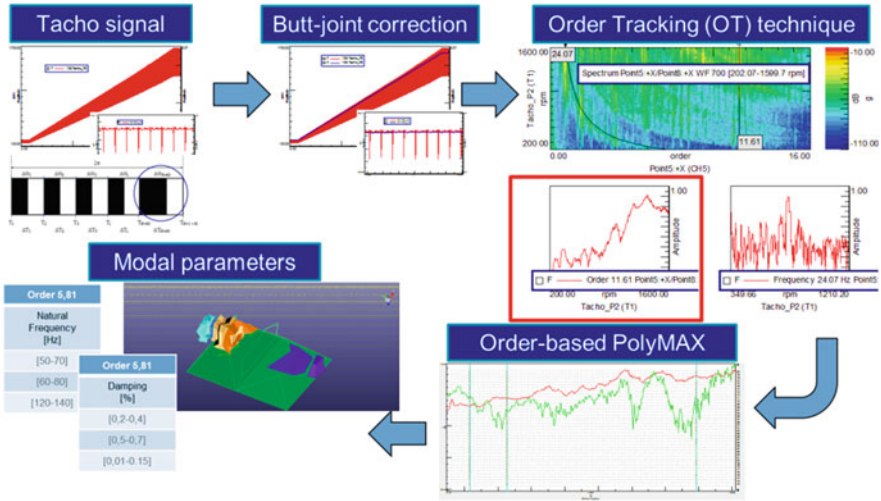


Fig. 10.8 Order-based Modal Analysis process overview

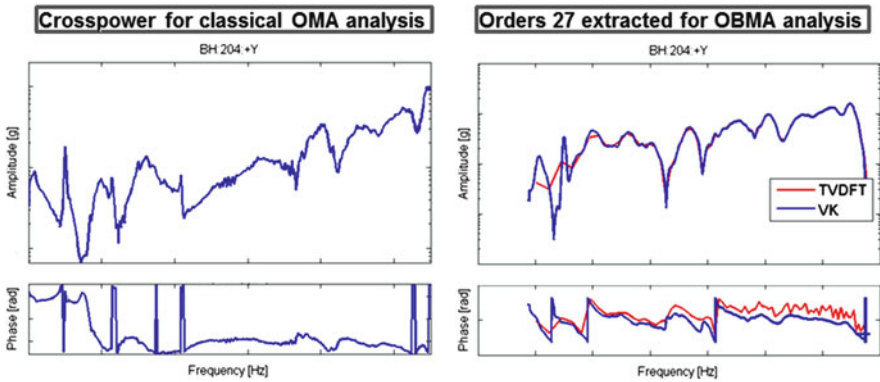
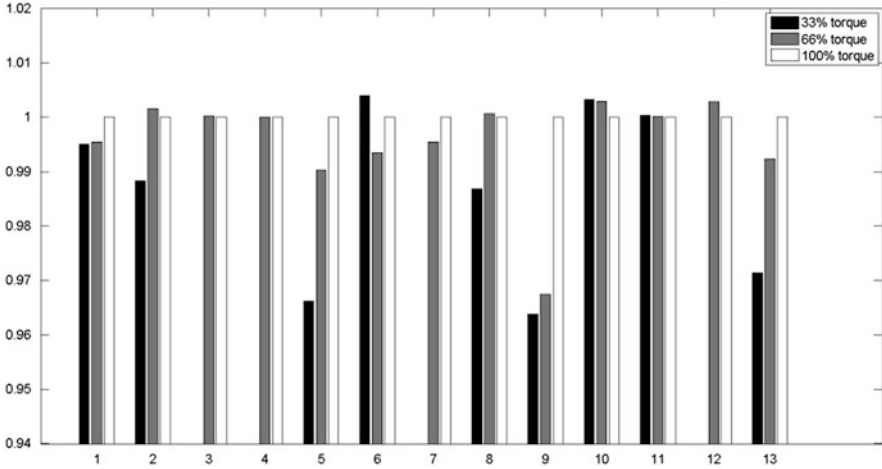


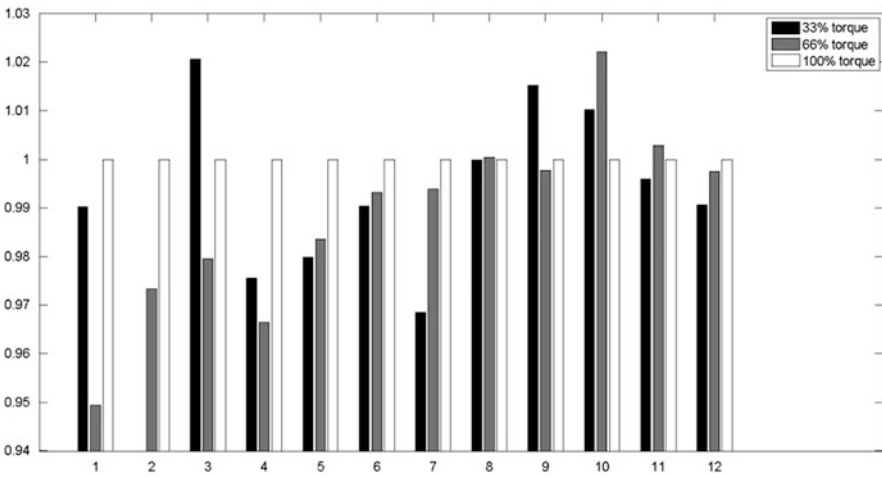
Fig. 10.9 Crosspower for classical OMA analysis (left) and 1st high speed gear stage order extracted by using two different order tracking techniques for OBMA analysis (right)

investigate possible system non-linearities resulting in variations of modal parameters. The results are summarized in Fig. 10.10, where the relative variations of the natural frequencies for the 3 cases (using as reference load case the one with 100% load) are displayed. The general trend from the results shows an increase of the natural frequencies with the torque value. Generally, almost all modes are consistently identified in the 3 load cases, but it should be noted that the majority of them actually represent “end-of-order” poles.

By first extracting the orders with the TVDFIT and VK tracking algorithms from the same time data and then using these orders for OBMA, the results shown in Figs. 10.11 and 10.12 are obtained.

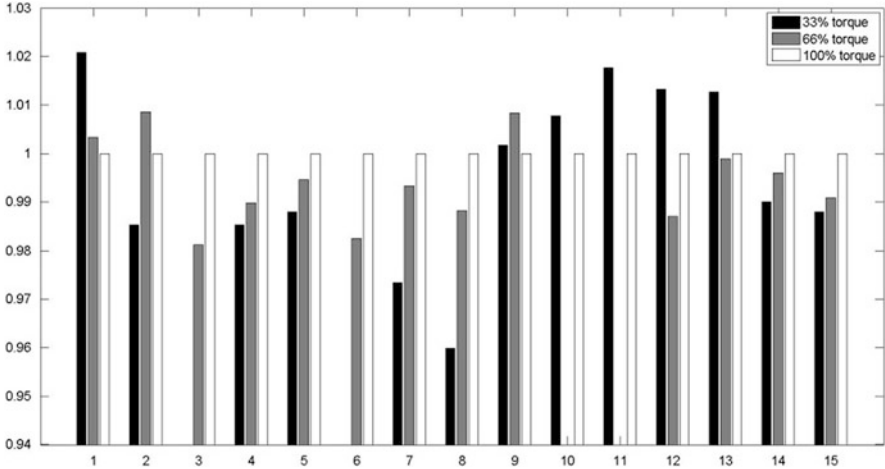


**Fig. 10.10** Operational Modal Analysis results on run up data—relative variation of natural frequencies with torque level

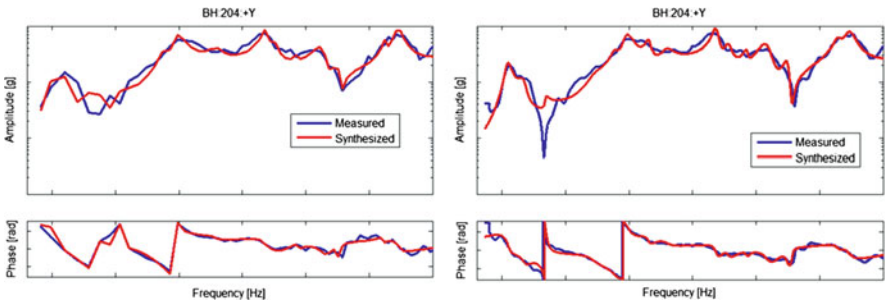


**Fig. 10.11** Order-based Modal Analysis with TVDFT order tracking—relative variation of natural frequencies with torque level

From the displayed results it is immediately clear that OBMA on the VK tracked orders is the process which identifies the highest number of modes. One way of validating the identification results is to compare the measured order with the one computed using the modal parameters in the parameterization of the system transfer presented in Eq. (10.13). The synthesized models from OBMA using the two selected order tracking techniques are shown in Fig. 10.13. In the mid-high frequency band, the identified modal models are able to accurately replicate the measured order. However, at lower frequencies, where the number



**Fig. 10.12** Order-based Modal Analysis with VK order tracking—relative variation of natural frequencies with torque level

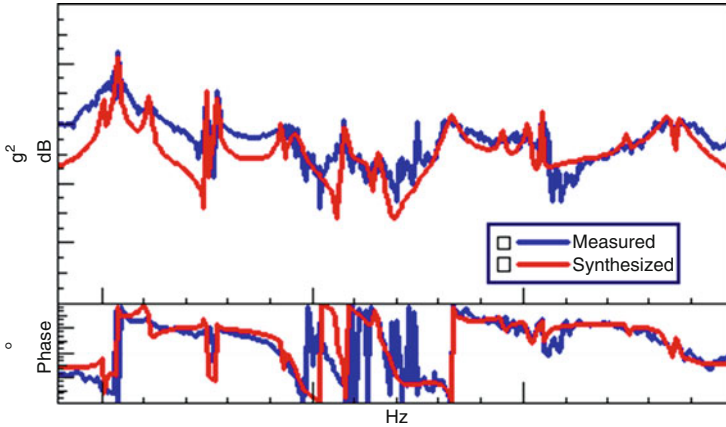


**Fig. 10.13** Measured vs. synthesized orders by using OBMA with TVDFT (*left*) and VK (*right*) order tracking

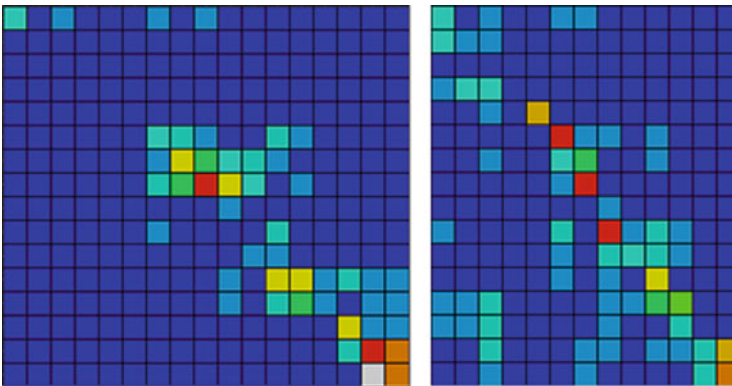
of available samples for the order estimation is typically smaller, VK as expected performs significantly better. By applying OMA on the data, the results displayed in Fig. 10.14 are obtained. The difference between the measured and synthesized curve is now immediately evident and the identified model is thus not able to represent the true measured response. Also, the majority of the identified peaks appear very sharp and they correspond to end-of-order poles.

Finally, a further comparison between the different methods can be performed by computing the Modal Assurance Criterion (MAC) between mode sets. The results for different combinations of mode sets are displayed in Fig. 10.15: values of MAC equal to 1 (Red) mean two modes are perfectly correlated, while a MAC of 0 (Blue) means the two vector are perfectly orthogonal.

The displayed results focus on the results obtained for the 100% load cases using the three different discussed methods. Only few modes are found to be similar



**Fig. 10.14** Measured vs. synthesized crosspower spectra using classical OMA



**Fig. 10.15** MAC comparisons. *Left*: OMA vs. OBMA-VK; *right*: OBMA-TVDFDFT vs. OBMA-VK

between OMA and OBMA and this is related to the high number of end-of-order poles identified. By comparing the results obtained using the two order tracking techniques, a discrete correlation is found for the modes in the mid-high frequency range. As expected from the results displayed also in Fig. 10.12, at lower frequencies the predicted orders differ significantly, thus a difference in the extracted modes is also expected.

Table 10.1 summarizes the differences between the analyzing order tracking techniques by analyzing:

- the input parameters the user has to define.
- the computational effort required for the estimation.



**Table 10.1** Critical assessment of the different analyzed order tracking techniques

Order tracking technique	Advantages & drawbacks
Angle Domain Order Tracking	Suitable for real-time processing Equidistant order lines Huge number of parameters to be set Great sensitivity of the resulting order on the settings Very noisy phase Modal parameter estimation is not reliable
Time Variant Discrete Fourier Transform	1 parameter to be set (number of rotation per order line) Computationally efficient Post-calculation to separate close and crossing orders Non equidistant order lines Low resolution at low frequency Phase smoothness depends strongly on the number of rotation per order line Difficult to fit higher frequency
Vold-Kalman Filter Order Tracking	2 parameters to be set (filter bandwidth and number of poles in the filter) Very high order resolution (number of lines equal to the number of acquired samples) Very good quality of the fit Beat free extraction of close and crossing orders Tracking capabilities are independent of the slew rate Non equidistant order lines Computationally demanding

The performed comparison also includes standard Angle-domain resampling order tracking. Although the results are not discussed here, the method is one of those most employed in industry and implemented in commercial solutions.

Figures 10.16 and 10.17 show the comparison between the same mode obtained by applying the OMA and OBMA techniques. In Manzato et al. (2015), the same results were also compared with the modes identified with shaker excitation. In terms of natural frequencies, the different techniques correlate very well.

On the other hand, damping values are more scattered, which is however expected with operational data. However, when comparing mode shapes using the Modal Assurance criterion, very poor correlation is observed although the shapes graphically compare. These results can be however be expected by taking into account the number of measurement points, the measurement and processing noise and uncertainties as well as the small inconsistencies between the different runs where the setup was changed.

Thus, at least when these conditions apply, it is envisaged to validate the analysis only qualitatively by comparing the mode shapes rather than performing a quantitative analysis based on the MAC.

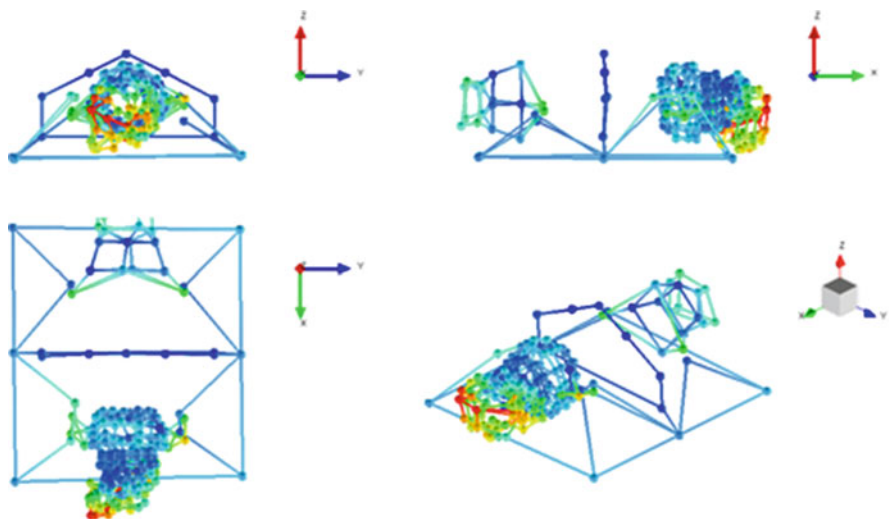


Fig. 10.16 OMA results—Deformed shape of mode #9

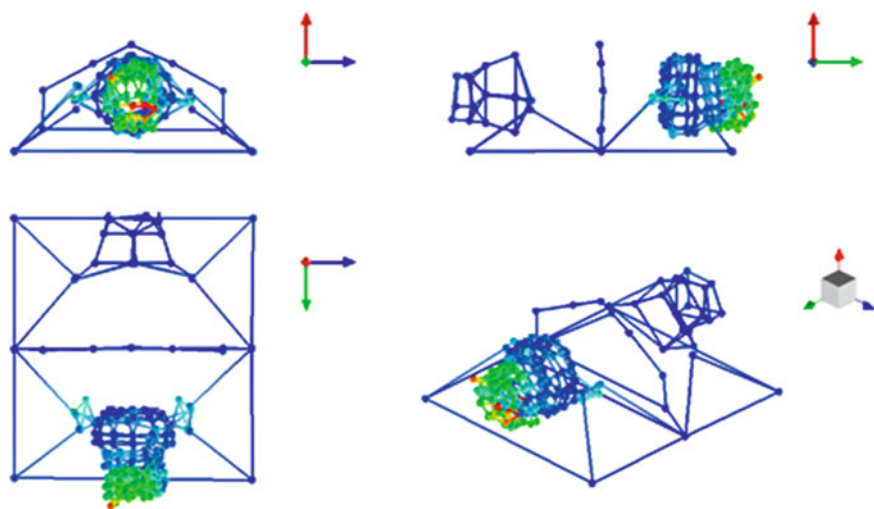


Fig. 10.17 OBMA-VK results—Deformed shape of mode #9

## 10.5 Conclusions

When analysing the dynamic response of rotating machines in operating conditions, the techniques developed to perform operational modal analysis don't hold. After clearly demonstrating that these methods don't provide reliable results both during

stationary and transient condition, a novel method is introduced, which is able to extract an operational modal model from run-up or run-down experiments.

Order-Based Modal Analysis (OBMA) relies on extracting high quality order from the throughput time data that can be then used for modal parameter identification using classical operational modal analysis algorithm. The advantages over classical Operational Deflection Shape (ODS) that also rely on order extraction are the possibility to clearly identify which part of the response can be associate to the system dynamics, which to the input forces and which to a combination of both. Moreover, damping information for each of the modes can be extracted and closely separated modes, as soon as the order resolution allows it, can be distinguished.

However, the use of an accurate phase reference signal is mandatory to obtain a reliable modal model and because of this an accurate tacho measurement is even more critical than in standard ODS analysis. Also, by using more advanced order tracking techniques, although sometimes computationally demanding, can lead to significant improvement of the results.

OBMA has demonstrated to be suitable for operational processing and to give very good results. The method was significantly improved and the two new methods (TVDFFT and VK) showed much improved results compared to older implementations. The extra effort compared to calculate the ODS are limited, although the Vold-Kalman order tracking is computationally more demanding and the quality of the tacho signal should be high enough to allow a reliable processing of the data. The results of the proposed approach were used in Vanhollebeke et al. (2015) to validate the operational response of the analysed gearbox predicted using a flexible multibody model.

**Acknowledgments** The authors would like to kindly acknowledge Frederik Vanhollebeke, Sonja Goris and Joris Peeters of ZF Wind Power for the possibility of using the data acquired on the gearbox test rig to carry out this research. Additionally, the authors kindly acknowledge the Institute for Promotion of Innovation through Science and Technology in Flanders, Belgium (IWT Vlandereen) for the O&O grant ALARM in which the aforementioned experimental campaign was performed. The ALARM project was furthermore supported by an Eureka label in the framework of international co-operations.

**Open Access** This chapter is distributed under the terms of the Creative Commons Attribution-NonCommercial 4.0 International License (<http://creativecommons.org/licenses/by-nc/4.0/>), which permits any noncommercial use, duplication, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license and indicate if changes were made.

The images or other third party material in this chapter are included in the work's Creative Commons license, unless indicated otherwise in the credit line; if such material is not included in the work's Creative Commons license and the respective action is not permitted by statutory regulation, users will need to obtain permission from the license holder to duplicate, adapt or reproduce the material.

## References

- Blough J (1998) Improving the analysis of operating data on rotating automotive components. Dissertation, University of Cincinnati
- Blough J, Brown DL, Vold H (1997) The time variant discrete fourier transform as an order tracking method. In: Publications: Technical Paper Number 972006. Society of Automotive Engineers. Available via SAE. <http://papers.sae.org/972006/>. Accessed 08 Apr 2016
- Carne TG, James GH III (2010) The inception of OMA in the development of modal testing for wind turbines. *Mech Syst Signal Pr* 24:1213–1226
- Goris S, Vanhollebeke F, Ribbentrop A et al (2013) A validated virtual prototyping approach for avoiding wind turbine tonalities. Paper presented at the 5th international conference on wind turbine noise, INCE-Europe, Denver, 28–30 August 2013
- Heylen W, Lammens S, Sas P (2013) Modal analysis theory and testing. KU Leuven, Belgium
- Janssens K, Kollar Z, Peeters B et al (2006) Order-based resonance identification using operational Polymax. In: Abstracts of the IMAC-XXIV: conference and exposition on structural dynamics – looking forwards: technologies for IMAC, Society for Experimental Mechanics, St. Louis, 30 January–02 February 2006
- Manzato S, White JR, LeBlanc B et al (2013) Advanced identification techniques for operational wind turbine data. In: Allemang R, De Clerck J, Niezrecki C et al (eds) Topics in modal analysis volume 7: proceedings of the 31st IMAC, a conference on structural dynamics, 2013. Conference Proceedings of the Society for Experimental Mechanics Series, Springer, New York
- Manzato S, Di Lorenzo E, Medici A et al (2015) Order-based modal analysis versus standard techniques to extract modal parameters of operational wind turbine gearboxes. In: Mains M (ed) Topics in modal analysis volume 10: proceedings of the 33rd IMAC, a conference and exposition on structural dynamics, 2015. Conference Proceedings of the Society for Experimental Mechanics Series, Springer, New York
- Peeters B, Van der Auweraer H, Vanhollebeke F et al (2007) Operational modal analysis for estimating the dynamic properties of a stadium structure during a football game. *Shock Vib* 11:395–409
- Vanhollebeke F, Peeters P, Helsen J et al (2015) Large scale validation of a flexible multibody wind turbine gearbox model. *J Comput Nonlinear Dynam*. doi:10.1115/1.4028600
- Vold H, Leuridan J (1993) High resolution order tracking at extreme slew rates, using Kalman tracking filters. In: Publications: Technical Paper Number 931288. Society of Automotive Engineers. Available via SAE. <http://papers.sae.org/931288/>. Accessed 08 Apr 2016