Chapter 1
The Energy Spectrum for the Detection of Harmonic Components in Ambient Vibration Tests

Mona Amer and Carlos E. Ventura

Abstract Operational modal analysis is a widely used technique to determine modal parameters from ambient vibration tests of civil and mechanical engineering structures. Speed-synchronous structural responses from rotating machines superimpose the ambient vibration responses and harm the successful identification of modal parameters. These so-called harmonics can be falsely identified as structural characteristics if not treated appropriately. A new technique for the identification of harmonics in ambient vibration data has been recently introduced and is discussed in more detail considering different applications such as an axial compressor, a wind turbine, and a ship. The mass-drawn energy spectrum is a measure used in earthquake engineering for the quantification of the energy introduced by ground motion. It can serve as a measure for potential structural damage. As harmonics have a much higher signal energy than structural modes, they can be distinguished in the frequency domain as sharp peaks. The proposed technique can thus be used to remove these components from the frequency spectrum before the consecutive modal analysis. The advantage is that frequencies, which do not result from the main rotation of the system but might be subjected to auxiliary equipment or the power circuit can be successfully identified as well. By means of the proposed approach, modal properties can be determined with greater confidence.

Keywords Operational modal analysis · Speed synchronous vibration · Earthquake engineering · Modal identification · Energy spectrum

Introduction

The modal identification of rotating machines in operation is still considered a challenge because speed-synchronous vibrations superimpose the measured output of a system in operation. These speed-synchronous vibrations, so-called harmonics, can be falsely identified as structural characteristics by established modal identification techniques if no appropriate action is taken. In the literature, various approaches to deal with these harmonics can be found. They can be categorized into four different types [1]. Statistical criteria, pre-processing techniques, extended identification methods, and input-independent identification techniques can be distinguished. Examples for these different types are the excess value [1], time-synchronous averaging [2], modified stochastic subspace identification [3], or transmissibility based operational modal analysis [4], just to name a few. These approaches were applied to systems under laboratory conditions or specific use cases with a unique set of operating conditions. Often limitations of the different procedures were experienced. For this reason, it is necessary to adapt an application-specific procedure, which takes into account the different boundary conditions of the system under investigation. A combination, which includes the identification and removal of harmonics, has proven successful when applied to a high-speed axial compressor [5]. A core quantity in this proposed technique represents the energy spectrum, which is a measure originally derived from earthquake engineering. It can provide insights into the presence of harmonics. Its effectiveness will be discussed more in detail using three different examples of application. The main advantage is that harmonics from other sources than the operated rotor can be identified as well, as will be shown in the results section.

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Methodology

The mass-drawn energy spectrum is a measure that is typically used in earthquake engineering. It classifies the energy introduced by ground motion into the structure and can be used as a measure for potential structural damage [6]. A single degree of freedom (DOF) system with the well-known equation of motion $\ddot{q} + 2D\omega\dot{q} + \omega^2 q = -\ddot{y}$, where D describes the damping, ω the natural circular frequency of the system, q the displacement of the excited single DOF system, respectively $\dot{q}$ the velocity, $\ddot{q}$ the acceleration, and $\ddot{y}$ the ground acceleration, is assumed. The mass-drawn input energy is defined as

$$E_I = \frac{E}{m} = \int_{-\infty}^{\infty} \ddot{y}\dot{q}dt, \tag{1}$$

with the energy E and the mass m. The velocity $\dot{q}$ can be calculated using different techniques. In this work, the numerical method proposed by Nigam and Jennings using a state-space representation is applied for the calculation. The single steps can be found in [7]. The calculation is based on time-discretized dimensions. To identify the harmonics, a low damping value, e.g. 1%, is assumed. The measured response acceleration of the structure serves as input for the ground acceleration $\ddot{y}$ in the previous equation. The procedure of calculating the energy spectrum for a single DOF system is depicted in Fig. 1.

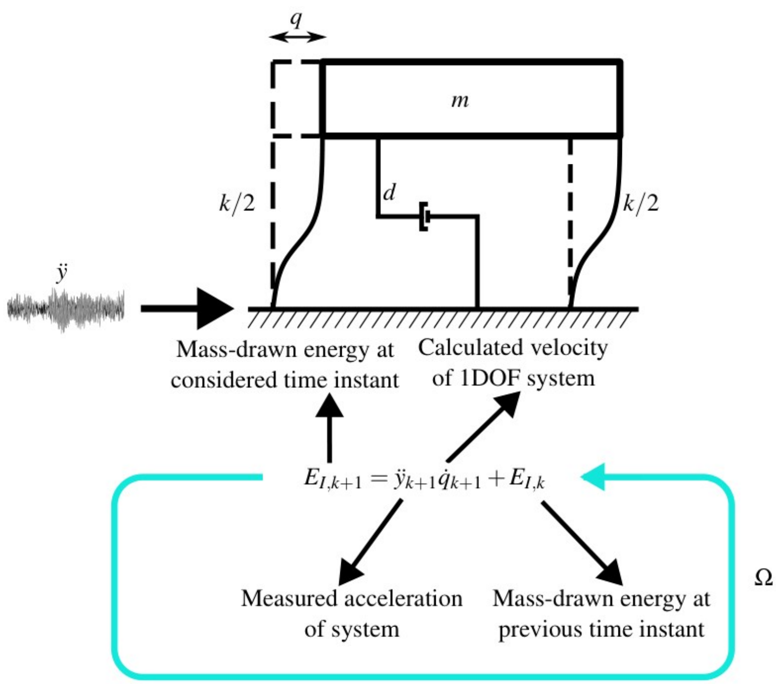


Fig. 1 Calculation of energy spectrum.

The different entities to calculate E_I are explained in Fig. 1. The blue arrow refers to the frequency range, for which the input energy is calculated so that the user obtains the energy spectrum in dependence of the pre-defined frequency vector. This can then be depicted as a function of the frequency in the frequency domain. The arrow can thus be interpreted as a loop, since the calculation is performed for each entry of the frequency vector. The single calculation steps are summarized as follows:

1. Calculation of the velocity $\dot{q}$, e.g. using the method by Nigam and Jennings [7],
2. Calculation of the discretized input energy $E_{I,k}$ at discrete time instants t_k over a designated frequency vector of interest: $E_{I,k+1} = \ddot{y}_{k+1}\dot{q}_{k+1} + E_{I,k}$,
3. Illustration of E_I dependent on the selected frequency range. The dominant peaks can be interpreted as disturbing signal components mainly from sources that cause harmonic vibrations.

The peaks in the energy spectrum represent the harmonics present in the operated system. The harmonics are characterized by a much higher signal energy than the structural modes and can thus be distinguished in the energy spectrum. This will be shown below by means of multiple use cases.

Results

The proposed method for the identification of harmonics is shown and discussed by means of three use cases that all consist of rotating components, more specifically an axial compressor, a wind turbine and a vessel in operation. In the following section, it is shown that harmonics can be identified unambiguously and efficiently using the proposed criterion.

Axial compressor

The axial compressor test rig, see Fig. 2, used for the following investigations consists of single stage rotor configuration with adjustable vanes and can be operated up to a nominal rotor speed of 17,100 rpm. The compressor has been operated and data has been acquired at different constant speeds as well as during run-up and run-down. The test rig has been equipped with 49 uniaxial acceleration sensors equally distributed over all the structure's components. The high sampling frequency of 25.6 kHz, which is needed for unbalance analysis in operation, is later downsampled, since the frequency range up to 150 Hz is of main interest. The critical speed of the rotor, representing a bending mode, is around 115 Hz. Details on the test setup can be found in [5]. Measurements for the constant speeds are usually three minutes long and for ramp-up and ramp-down around seven minutes long. The focus in the following analysis is on the constant rotational speeds, since the data from the ramp-downs and ramp-ups can be only analyzed in sections due to the large data size. Calculating the energy spectrum for a section of the run-down, will only show the mean rotational frequency during this duration as the dominant peak in the energy spectrum. Since the rotational speed is constantly varying, the peak is wide-banded showing a frequency content of multiple rotational frequencies around the mean rotational frequency. Analyzing a longer duration of the run-down shows the maximum rotor speed of 17,100 rpm or 285 Hz to be the most dominant peak, since the rotor speed changes slowly in the beginning of the run-down.

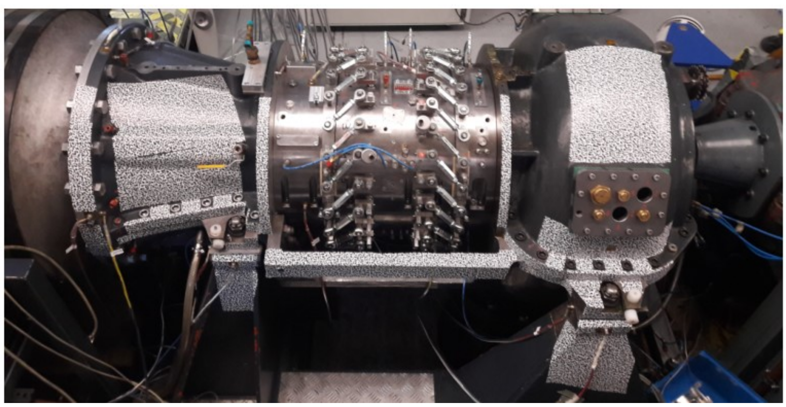


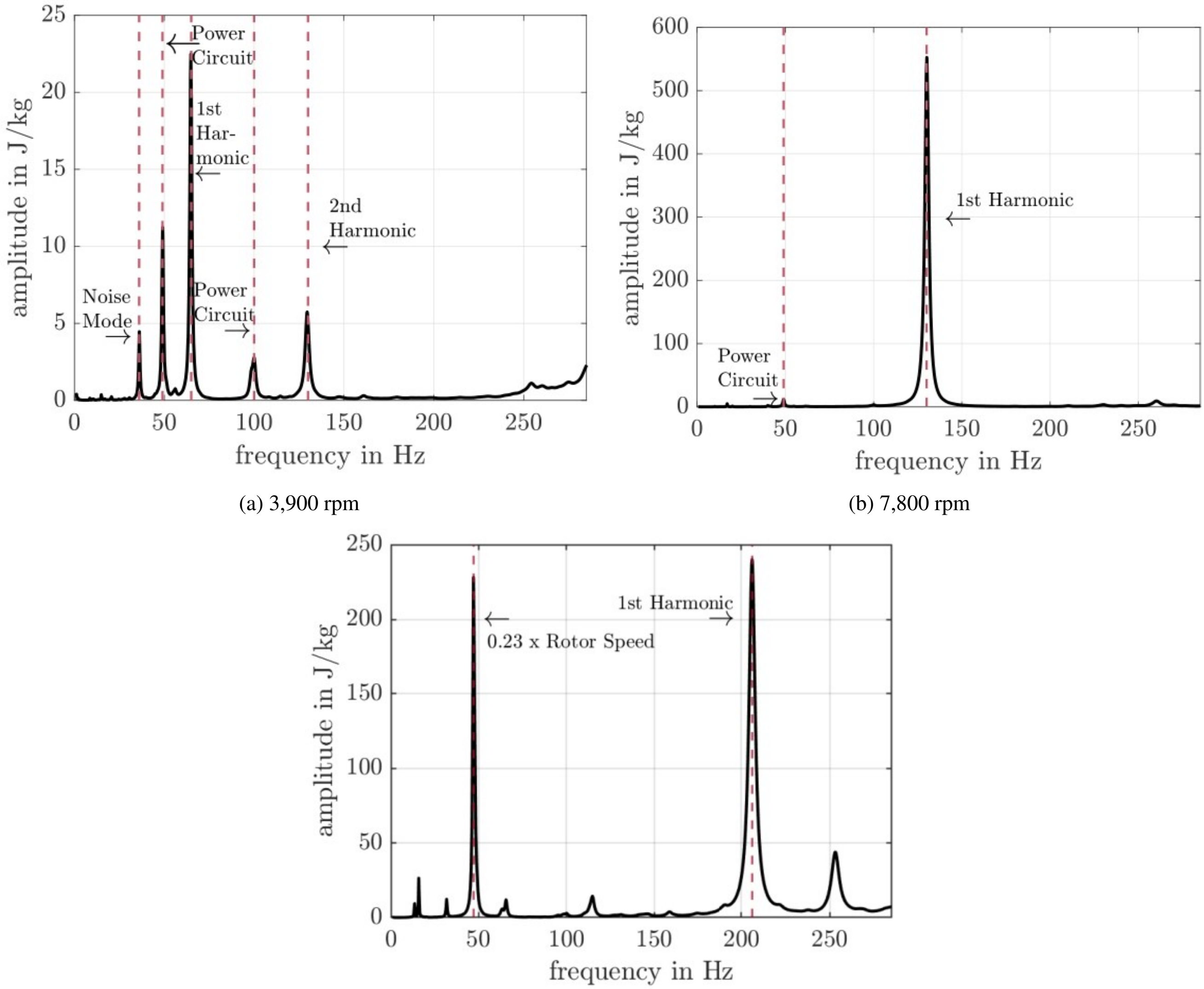
Fig. 2 Axial compressor test rig at the Institute of Turbomachinery and Fluid-Dynamics, Leibniz University Hannover.

In Fig. 3, the calculated energy spectrum is compared for three different constant rotational speeds. At first, the energy spectrum is calculated for each channel individually and can then be averaged over multiple sensors to capture a more representative behavior of the harmonic influence in operation. In the following case, it is averaged over nine sensors representing all instrumented components of the compressor test rig.

The first harmonic can be clearly identified for all three depicted rotational speeds and has been labeled accordingly. For the rotational speed of 3,900 rpm, other influences are visible in the energy spectrum. Since the structure couldn't be completely electromagnetically isolated, the power circuit acts as a source that causes harmonic response vibrations. For this reason, the user can observe dominant peaks at 50 Hz and 100 Hz (respectively the first and second harmonic of the power frequency in Europe). An additional dominant peak is visible in the lower frequency range. It also plays a role in the modal identification, since it is detected as a stable mode by the algorithms, but it does not represent a physical mode. Further investigations reveal that this frequency belongs to a local mode of the foundation, which should not be mistaken as a system mode and can thus be ignored in the data evaluation. This frequency, therfore, represents a noise mode.

The power frequency plays a less significant role for higher rotational speeds, since the signal energy of the first rotor harmonic is much more dominant, as can be seen in Fig. 3b looking at the high amplitudes of nearly 600 J/kg. Therefore, other influences than the first rotor harmonic don't play a role in this data set.

In Fig. 3c, next to the first rotor harmonic, a second effect becomes recognizable. This belongs to the third harmonic of the motor, which causes harmonic response vibrations of the system. Through the gearbox ratio of 1:13, this is transformed



(a) 3,900 rpm (b) 7,800 rpm

(c) 12,360 rpm

Fig. 3 Energy spectrum of three different rotational speeds of the axial compressor investigated.

to 0.23 × first harmonic of the rotor, which the user can observe in the energy spectrum. This frequency has been already observed in the tip timing system used for the vibration analysis of the turbomachinery blades in operation. Due to the energy spectrum, this frequency can be excluded from the modal identification. This is especially important for even higher rotational speeds, since this frequency gets closer to the first natural frequency of the system and can thus be easily mistaken as a structural mode.

It is remarkable that each rotor speed investigated leads to a different amplitude level of the highest peak in the energy spectrum. This fact underlines that each relevant operating point should be studied individually and that there is no general cutoff value, which differentiates between structural mode and harmonics. However, it can be stated that all significant peaks in the studied energy spectra of the axial compressor belong to disturbing effects and do not represent a structural characteristic of the system. The advantage of this method is that it can also identify harmonics, which are associated with other sources than the rotor of the main system like auxiliary units with rotating components or the power circuit.

Wind turbine

The second data set is derived from a wind turbine, which is operated in the South of Chile. It was equipped with four triaxial velocity sensors from Tromino, which can be used for seismic measurements. A schematic setup of the sensors is depicted in

Fig. 4. The data was acquired during a 20 hours test with a sampling frequency of 128 Hz. The rotational speed information is sparse, since there is only one time stamp each ten minutes. Therefore, the sections chosen for the analysis can contain rotor speed variations. For the analysis, data sections were selected that had the same average rotor speed for more than two consecutive time stamps to ensure a sufficient length of the data set. For the analysis, two data sets with an average rotor speed of 9 rpm over 30 minutes and 10.5 rpm over 80 minutes were used. The energy spectrum resulting from this data is depicted in Fig. 5.

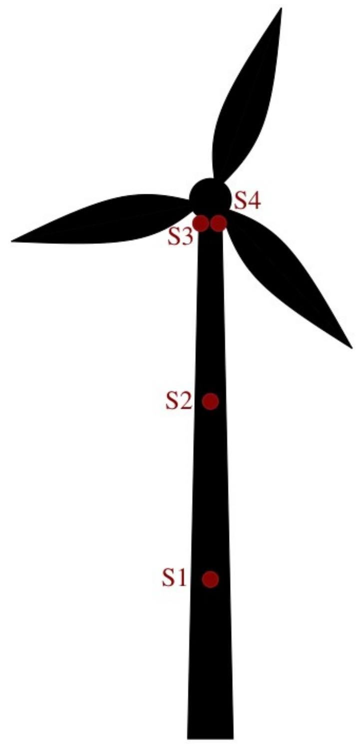


Fig. 4 Sensor setup on wind turbine.

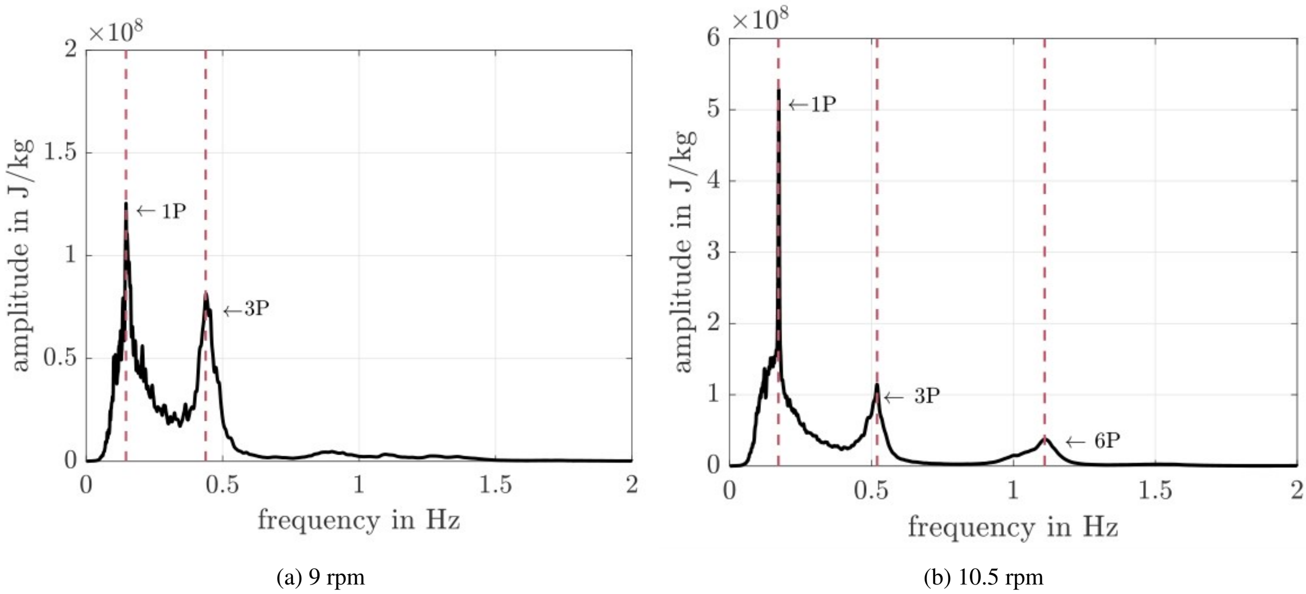


Fig. 5 Energy spectrum of three different rotational speeds of the wind turbine investigated.

The energy spectrum is averaged over all four sensors taking into account each of the channels measuring in North-South direction. In this data, the first, third, and sixth harmonic, also called 1p, 3p, and 6p in case of a wind turbine, are dominant. As expected, the influence of the first rotor harmonic and the third one according to the number of blades have the strongest superimposing character on the data. Other effects do not seem to play a dominant role for this use case. A rotor speed variability can be observed on the basis of the wide-spread peaks in the frequency domain in Fig. 5. The amplitude level of the input energy is more than 3×10^5 higher than the previous use case investigated. This fact demonstrates the strong influence of the rotation in the data and the necessity for appropriate tools to deal with these influences, since the harmonic frequency content is close to structural frequencies that have been identified in standstill condition without any rotation.

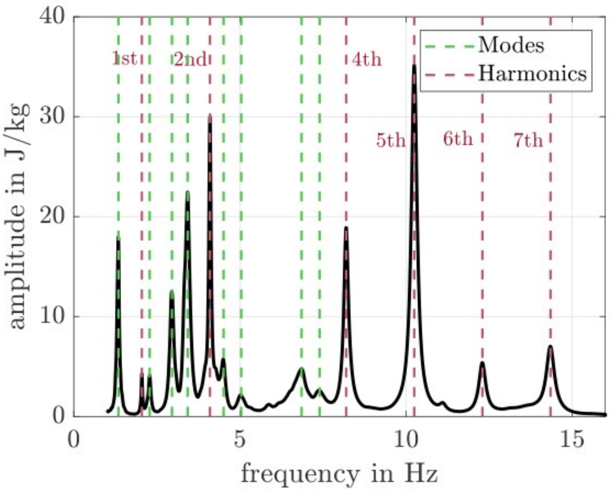
Ship

Next, data from a ship, shown in Fig. 6, excited by the running engine, is analyzed. The ship has a four bladed propeller with a controllable pitch and is equipped with 16 uniaxial sensors collecting data for a duration of 90 minutes with a sampling frequency of 128 Hz. It is, thus, expected to see a dominant influence of the first and fourth harmonic due the number of blades.

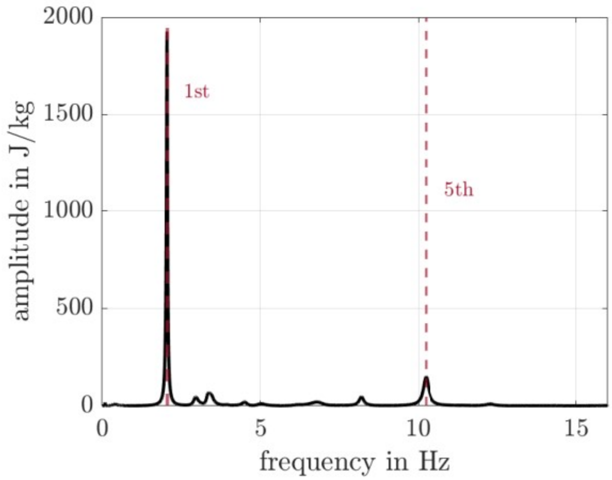
Fig. 6 Ship excited periodically from running propellers [8].

The influence of the different harmonics is represented by four different sensor channels in Fig. 7. On the one hand, strongly varying amplitude levels can be observed for the different channels. On the other hand, for each sensor other harmonics play the most dominant role in the energy spectrum. The distance of the sensor from the engine plays a significant role for the influence of the harmonics in the captured data. Channel 1 shows that the harmonics have a comparable influence as the structural modes. The signal energy of the harmonics is, in this case, not much higher than that of the structural modes and can thus not be distinguished from the structural components in the measured data. This looks very different for Channel 2, Channel 7, and Channel 8, also represented in Fig. 5. For these channels, only the influence of the harmonics resulting from the running propeller are dominant in the energy spectrum. Channel 2 in Fig. 7b shows the most significant influence resulting from the first rotor harmonic and a much more reduced influence from the fifth harmonic. In channel 7, the most significant influence comes from the fourth harmonic indicating that the sensor is located close to the propeller and the four blades lead to the strong influence that can be observed. The amplitude of the fourth harmonic is also more than four times higher than the amplitude of the first harmonic for channel 2. A mixture of the influence of multiple harmonics, can be observed for channel 8 in Fig. 7d. Next to the first harmonic, which is the most dominant, the fourth, fifth, and sixth harmonic can be clearly identified from the energy spectrum and will likely have an influence on the modal identification of this data.

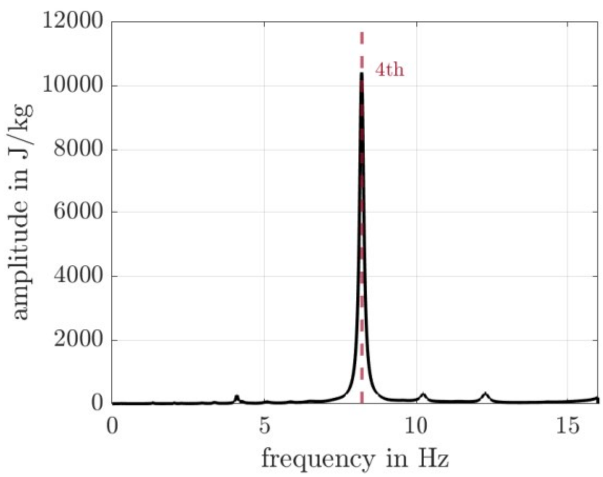
In Fig. 8, the energy spectrum is represented as an average of six channels according to the previous application cases. Similarly to the results from channel 8, four dominant harmonic frequencies can be distinguished. As Fig. 8 represents an average, the amplitude level of each harmonic signal varies compared to the results from channel 8. The fourth harmonic, corresponding to the number of propeller blades, has the highest amplitude level. The comparison between the energy spectrum calculated for single channels depicted in Fig. 7 and an average over multiple, characteristic channels in Fig. 8 underlines the benefit of such an illustration, since single channels might not be representative for the influence of the



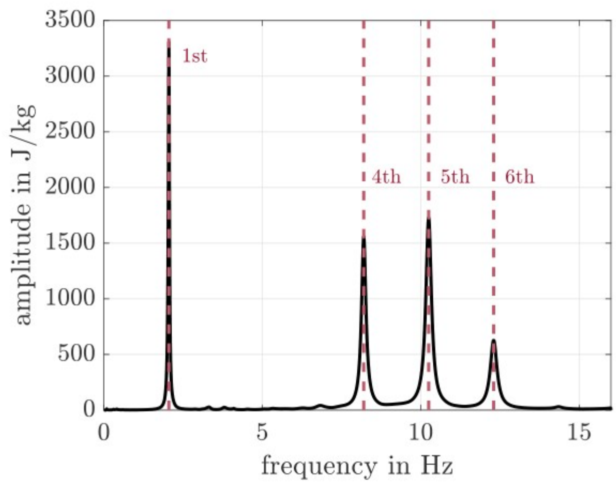
(a) Channel 1



(b) Channel 2



(c) Channel 7



(d) Channel 8

Fig. 7 Energy spectrum of ship with running propellers calculated for four different sensor channels – green dotted lines represent structural modes; red dotted lines represent harmonics.

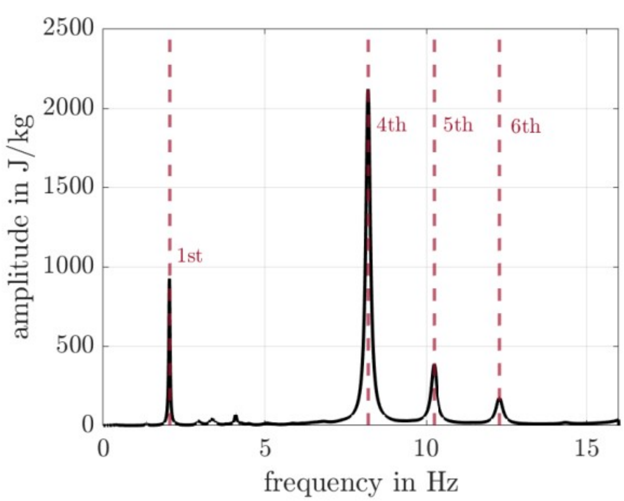


Fig. 8 Energy spectrum calculated from the ship data averaged over six channels.

harmonics on the overall structural behavior, see Fig. 7a. Considering a single channel can be misleading, since the influence of harmonics can be underestimated or overestimated. The influence of the harmonics is also evident when performing the data analysis since they can be clearly identified as thin sharp peaks in the power spectral density of the measured signal, cf. [8].

Comparison

From all of the three use cases, it can be observed that the influence of harmonic signal content in the measured structural responses can be clearly identified by means of the energy spectrum, described in the methodology section. It can be concluded that there is no generalized cutoff value for the amplitude, which decides whether a peak belongs to a harmonic or not. The amplitude of the peaks depend on the energy level of the harmonic vibrations for the individual use case. In comparison to other criteria like the probability density function, which can assess whether a selected mode is truly a structural mode or a harmonic, the energy spectrum is unambiguous at least when sufficient channels are considered. Taking the average over multiple test channels is therefore recommended to obtain a reliable representation. The energy spectrum therefore represents a supplement to the existing tools, which deal with harmonic system responses in ambient vibration tests.

Conclusions

A criterion for the distinction of harmonic signal content in measured structural responses usually used as input for operational modal analysis has been introduced and applied to different applications of machines. Three use cases of systems with rotating components in operation have been analyzed by means of the energy spectrum to obtain an insight into the harmonic effects present in the data. Depending on the application, the amplitude level of the calculated input energy for a single degree of freedom system will vary as it can be concluded from the comparison of the three use cases. Overall, the dominant harmonic frequencies superimposing the stochastic response could be clearly identified using the energy spectrum. In conclusion, there is no need for a cutoff value to differentiate between structural modes and harmonics, since the harmonic signal energy exceeds the level of structural modes by far. The reliable identification of harmonics will allow a robust extraction of modal parameters by means of well-established techniques for the modal identification of systems in operation.

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