IOMAC'15

6th International Operational Modal Analysis Conference

2015 May12-14 Gijón - Spain

A HARMONIC PEAK REDUCTION TECHNIQUE FOR OPERATIONAL MODAL ANALYSIS OF ROTATING MACHINERY

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ABSTRACT

In the case of rotating machinery that is operating at constant rotational speed, Operational Modal Analysis is sometimes a challenge due to the presence of significant harmonic peaks. In many cases, the rotating components affect the full frequency range being analysed due to the presence of additional orders.

In this paper, a harmonic peak reduction method is presented. The method directly subtracts the harmonic content from the raw time signal. A Gauss-Newton fitting algorithm is used to find the least square reduced fitting of the measurement data to a harmonic deterministic function.

The method is tested on two examples. The first is a simple aluminium plate excited with random as well as sinusoidal excitation. In this case, the harmonic peaks are completely removed. The second example consists of noisy measurements from a Prolec GE transformer. In this case, the harmonic reduction method is capable of reducing the harmonic peaks with more than 40 dB on an average.

Keywords: harmonics, data reduction, generator

1. INTRODUCTION

Operational Modal Analysis (OMA) is today a widely used technology for extracting modal parameters from structures during operation. OMA has extended the number of applications for modal analysis extensively over the last two decades since the first commercial software solutions were introduced. Today, OMA is a natural technology in civil engineering for e.g. ambient vibration tests and Structural Health Monitoring.

The technology has also gained interest in mechanical engineering. Especially after the introduction in 2006 of algorithms that can work in the presence of harmonic peaks arising from rotating parts, OMA has found its way to the rotating machinery industry [2][3][4].

In the case of rotating machinery operating at constant rotational speed, the challenges with the harmonic peaks are biggest. In many cases, the constant rotation results in several high peaks that in many cases have much more energy than the modes of the structure. One of two approaches, that has been applied in general for these cases is; either the algorithms are told to disregard the content at certain frequencies that have been detected prior to the modal analysis (harmonic detection) [1][2][3][5], or the algorithms have been made robust to the presence of the harmonics, like in the case of the Crystal Clear SSI estimator [6].

What we propose in this paper is a third approach that, combined with one of the other two, will lead to an even better performance in the cases of rotating machinery running at constant speed. The new method proposed is to subtract directly the harmonic content from the raw time signal. Therefore, a numerical Gauss-Newton fitting algorithm is used to find the least square reduced fitting of the measurement data to a harmonic deterministic function.

The new approach for reducing the harmonic peaks is tested on two examples. The first is a simple aluminum plate excited with random as well as sinusoidal excitation. The second example is measurements from a Prolec GE transformer.

2. THE REDUCTION TECHNIQUE

The harmonic function is usually disturbing the signal for an operational modal analysis which is based on random signals. The positive fact is that a harmonic disturbance is a certain kind of deterministic content.

The main idea of the method proposed is to find a deterministic function that fits as good as possible to the measurement data and then simply subtract it from the signal. In general, the time signal $y(t)$ will be modified to

$$\tilde{y}(t) = y(t) - [a_1 \cos(\omega\, t) + a_2 \sin(\omega\, t)] \qquad (1)$$

So for a removal of one single-frequency harmonic content there are three parameters a_1, a_2, ω that have to be identified. For this, the Gauss-Newton method is appropriate to solve the nonlinear optimization problem.

2.1. The Gauss-Newton Method

The algorithm as explained in [7] is outlined in the following. There is an observation of data l_i that are the sampled data of the vibration measurement. The residuum of the deterministic function f versus the observation is

$$r_i = f_i(x_1, x_2, \dots, x_n) - l_i \qquad (2)$$

with i observation points. x_j are the unknown parameters of the function. To gain the minimum of the quadratic error is the target:

$$F(x) = r^T \cdot r = \sum_{i=1}^{N} [f_i(x_1, x_2, \dots, x_n) - l_i]^2 . \qquad (3)$$

The minimum for the error requires that all derivatives with regard to the parameters are zero:

$$\frac{\partial F}{\partial x_i} = 0 \qquad (4)$$

The derivatives of the setup function are calculated analytically and implemented in the code. This is usually a nonlinear equation that cannot be solved directly. So the method to overcome this is a linearization of the parameter:

$$x_j = x_j^{(0)} + \xi_j \qquad (5)$$

The new residuum ρ is then

$$\sum_{i=1}^{N} \frac{\partial f(x_1^{(0)}, \dots, x_n^{(0)})}{\partial x_i} \xi_i + f_i\left(x_1^{(0)}, x_2^{(0)}, \dots, x_n^{(0)}\right) - l_i = \rho^{(0)} \qquad (6)$$

The reduction of the quadratic error F can now be written as a linear error equation:

$$C^{(0)} \cdot \xi - d^{(0)} = \rho^{(0)} \qquad (7)$$

The matrix $C^{(0)}$ contains the elements

$$c_{ij} = \frac{\partial f(x_1^{(0)}, \dots, x_n^{(0)})}{\partial x_i} \qquad (8)$$

and the vector $d^{(0)}$ is the vector of the residuals

$$d_i^{(0)} = f_i\left(x_1^{(0)}, x_2^{(0)}, \dots, x_n^{(0)}\right) - l_i. \qquad (9)$$

The linear equation for the error can be solved by the standard least square method for

$$C \cdot x - d = r \qquad (10)$$

which is the linear system of equations

$$(C^T \cdot C) \cdot x = C^T d. \qquad (11)$$

As the primary error reduction was nonlinear, the solution of the linear derivative will not lead to the final optimum. Therefore, iteration will be necessary. After each iteration, the solution is updated by

$$x_j^{(1)} = x_j^{(0)} - \xi. \qquad (12)$$

Additionally, it is normally not guaranteed that the iteration will find the optimum. It is required that the start values are somehow close to the solution.

2.2. Application to OMA Data

As stated before, the start values should be selected properly. For a harmonic function it will be mandatory for the process that the frequency is nearly met. In practice, it is easy as the frequency is known from the FFT of the signal. Within a usual FFT resolution, the start value is taken from the FFT or is known in advance e.g. from the grid frequency of a generator. It is recommended to use one value for the frequency for all channels of the measurement. One preferred method is to use the sum of all measured channels for the determination of the very precise frequency of the harmonic. If the signal is completely stationary, then the 3 parameters a_1, a_2, ω are sufficient. For long recordings slight changes of e.g. the rotational speed can be covered by a modified setup of a linear moving frequency

$$\tilde{y}_\Sigma(t) = y_\Sigma(t) - \left[a_1 \cos\big((\omega + \omega_\omega t) \cdot t\big) + a_2 \sin\big((\omega + \omega_\omega t) \cdot t\big)\right]. \qquad (13)$$

The frequency is now used as a fixed parameter for all other channels. For these channels, only the amplitudes have to be determined. An iteration of a_1, a_2 might be sufficient for each channel, but slight changes can again be covered for example with a polynomial change of the amplitude.

$$\tilde{y}_i(t) = y_i(t) - \big[(a_1 + a_3 t + a_5 t^2 + a_7 t^3 + a_9 t^4) \cos\big((\omega + \omega_\omega t)\, t\big) + (a_2 + a_4 t + a_6 t^2 + a_8 t^3 + a_{10} t^4) \sin((\omega + \omega_\omega t)\, t)\big] \qquad (14)$$

In principle, other setups can be used if information about the signal behavior is known. The data used for the harmonic reduction should be as stationary as possible, e.g. no bumps etc. Then a nearly 100% reduction of the harmonics is possible. Each harmonic is covered individually so that the algorithm with about 10 channels with >100,000 samples may take some minutes of computation time on a PC.

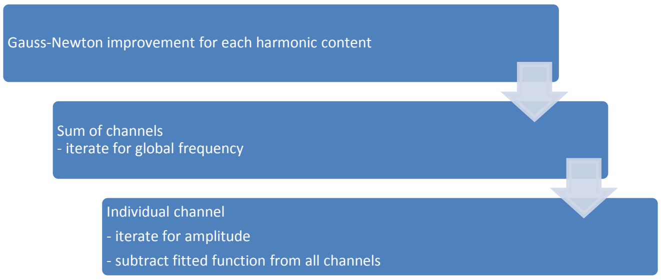

Figure 1. Workflow of harmonic reduction.

The method has been implemented in the ARTeMIS Modal Pro 3.5 software for Operational Modal Analysis [8], and in the following two sections examples of its efficiency are demonstrated.

3. EXAMPLE 1 – PLATE WITH HARMONICS

Plate with Harmonics example has been extensively used in the literature for studying harmonic detection and verification of OMA techniques robust to the presence of harmonic peaks [1],[2]. In figure 3.1 below, the test that was performed is presented. As shown, there are 16 accelerometers mounted in a 4 by 4 grid. In addition, there is a shaker mounted that introduces a sinusoidal excitation at 374 Hz. During the measurement period of 60 seconds, the plate was also excited by a random tapping. Sampling frequency was 4096 Hz.

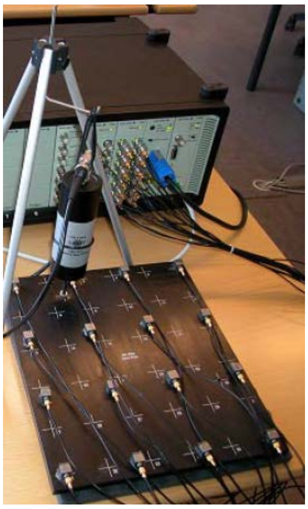

Figure 2. Test of a rectangular aluminum plate with 16 uni-axial accelerometers positioned in a 4 by 4 grid.

A time-frequency spectrogram reveals the constant harmonic excitation as well as the more random tapping that was applied. In figure 3.2, the spectrogram of one of the channels is shown.

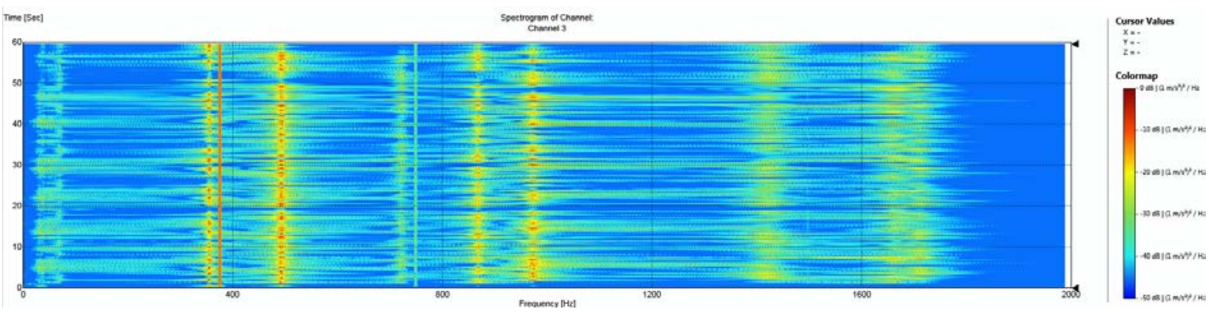

Figure 3. Time-frequency spectrogram of one of the channels.

Similarly, the structural modes and harmonic peaks can be viewed conveniently in a Singular Values diagram obtained from the spectral densities, see figure 3.3 below.

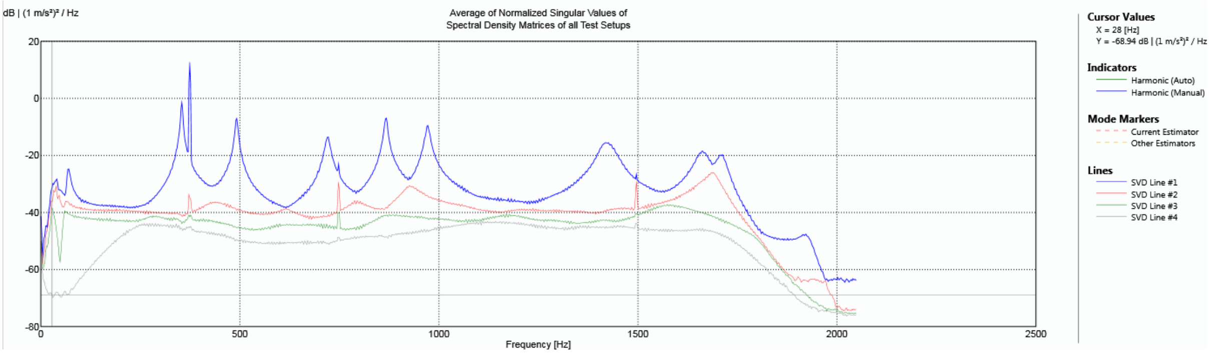

Figure 4. Singular values of the spectral densities of the 60 seconds measurements. Peaks from modes as well as harmonic components are easily identified in the type of diagram.

The first harmonic peak at 374 Hz and the next three orders were all selected for reduction. This can be seen in the Singular Values diagram of the spectral densities shown in figure 3.4.

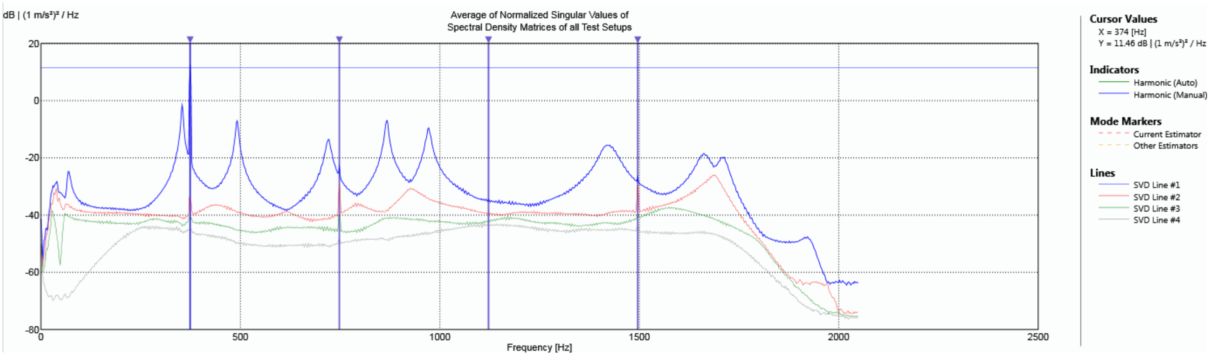

Figure 5. Selection of the four harmonic peaks to reduce.

In order to avoid startup problems that could violate the assumptions for the harmonic reduction, the first 5 seconds of the measurements are excluded from the reduction process. The reduction process lasts for about 2 minutes for the four harmonic peaks, and the modified measurements are then reprocessed as seen below in figure 3.5, with good results. All harmonic peaks have been removed in this case.

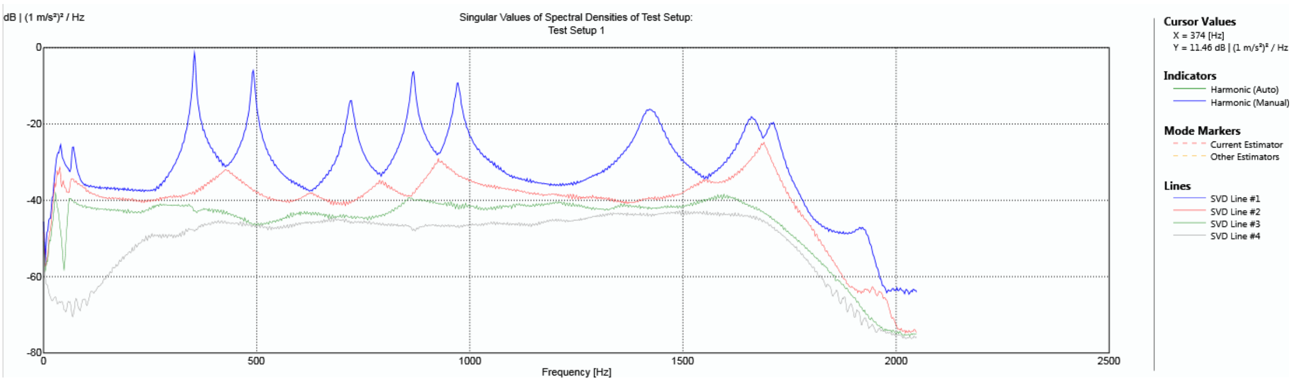

Figure 6. Singular values of the spectral densities of the modified measurements after harmonic reduction.

4. EXAMPLE 2 – PROLEC GE TRANSFORMER

The harmonic reduction algorithm has been tested with data acquired from a Prolec GE transformer with severe harmonic peaks at 60 Hz and multiples of that frequency. Prolec GE, located in Monterrey, Mexico, is one of the largest transformer manufacturers in the Americas, offering a complete line of transformer products necessary for the generation, transmission, and distribution of electric power. Prolec GE has over 30 years of experience in the industry, with products installed in more than 35 countries around the world.

The data has around 80 dB dynamic range from the highest harmonic peak and then down to the noise floor. Since the modal response is not more than maximum 15 dB above the noise floor, it makes any modal analysis difficult. Harmonic reduction is applied to at least "equalize" the heights of the harmonic and modal peaks.

Below in figures 7 and 8, the Singular Value Decomposition of the spectral densities of the transformer data can be seen before and after the harmonic reduction of the harmonics peaks at 60 Hz, 120 Hz, 180 Hz and 240 Hz, has been applied.

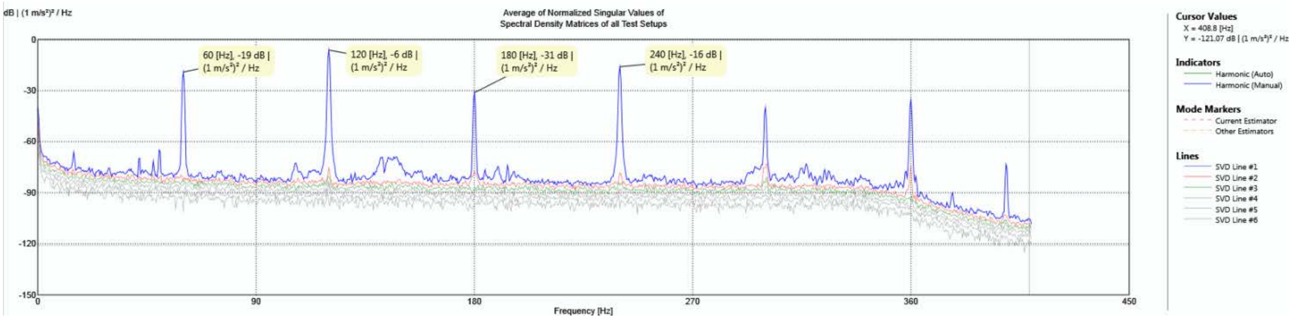

Figure 7. Singular Values of the spectral densities of the Prolec GE transformer data before harmonic reduction.

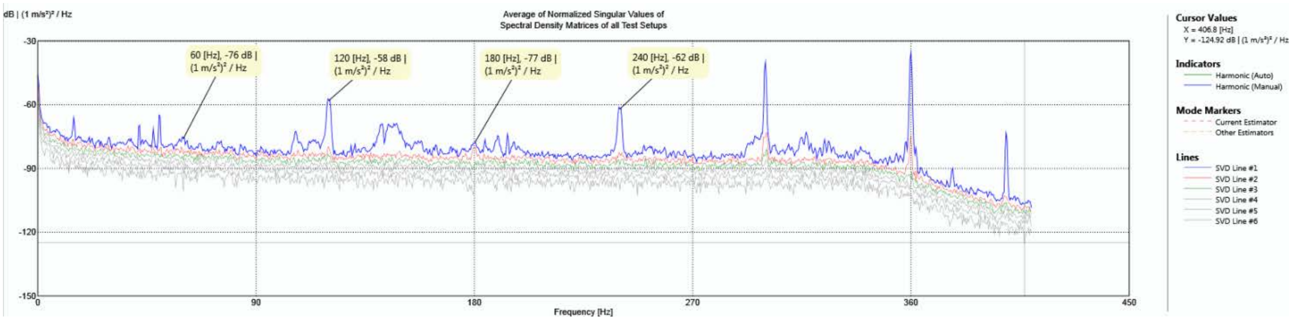

Figure 8. Same measurements after harmonic reduction of peaks at 60 Hz, 120 Hz, 180 Hz and 240 Hz.

Since the data has been acquired on the shielding outside the core of the transformer, there is a significant measurement noise, but even so the harmonic reduction is capable of reducing the harmonic peaks with more than 40 dB on an average.

5. CONCLUSIONS

In this paper, a harmonic reduction method has been presented. The method directly subtracts the harmonic content from the raw time signal. A Gauss-Newton fitting algorithm is used to find the least square reduced fitting of the measurement data to a harmonic deterministic function.

The new approach for reducing the harmonic peaks has been tested on two examples. The first is a simple aluminum plate excited with random as well as sinusoidal excitation. In this case, the harmonic peaks are completely removed. The second example consists of noisy measurements from a Prolec GE transformer. In this case, the harmonic reduction method is capable of reducing the harmonic peaks with more than 40 dB on an average.

The developed method works best in case of completely constant harmonic excitation. This makes the method applicable for applications related to e.g. power production and production units running at constant RPM. Further work on this topic will aim at developing more adaptive methods that can accommodate for slight changes of both harmonic frequency and amplitudes.

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