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## Ambient suppression in vibration bump test using wavelet-based filter

C K E Nizwan<sup>1,\*</sup>, M F Ghazali<sup>1</sup> and A R Yusof<sup>1</sup>

Faculty of Mechanical & Manufacturing Engineering, Universiti Malaysia Pahang

\*Corresponding author: eddy@ump.edu.my

**Abstract.** Modal analysis is generally used to determine the structural dynamic characteristics of a system through experimental. The main purpose of a modal analysis is to identify the modal parameter, which consists of natural or resonant frequencies, mode shapes and damping. However, this technique required all the system in shut down condition in order to perform modal testing. The presence of ambient force such as motor unbalanced can cause errors in measurement of time response. Therefore, a study on how to improve the quality of the acquired signals in EMA is crucial in order to increase the efficiency of EMA technique under the presence of ambient force. This paper introduces a method to eliminate the ambient component in measured vibration response using the wavelet-based filter. The two experiments have been carried involving two different conditions, shutdown condition and operating condition. The sources of the ambient in operating condition are induced from a motor and speed controller cooling fan. The proposed method utilizes the discrete wavelet transform (DWT) and improvised spectral subtraction in filtering the ambient. The discrete wavelet transform (DWT) is applied to both ambient data and total response data to decompose the signal by a factor of two into several levels of the wavelet decomposition. The modification of the discrete wavelet transform (DWT) method has been done where the wavelet thresholding is replaced with the spectral subtraction to suppress the ambient in the signal. The spectral subtraction is used to suppress the ambient in each wavelet coefficient at each level of decomposition to avoid the losses of useful signal data while filtering the ambient. The decomposed wavelet signal is reconstructed and the result is being compared with the baseline data. The Frequency Response Function obtained from the reconstructed signal shows the harmonics feature from ambient excitation were successfully suppressed. The results show that the proposed approach is effective to suppress the ambient effect in vibration response measurement.

**Keywords.** Modal Analysis, Vibration Measurement, Wavelet Transform, Filter, Ambient suppression.

### 1. Introduction

Modal analysis is the most influential vibration analysis tool that is applied to determine the structural dynamic characteristics of a system [1]. The main purpose of a modal analysis is to identify the modal parameter [2]. Modal parameters obtained from the measured vibration data can be classified as the structural dynamic characteristics of the system. The modal parameter is obtained from the frequency response function. The frequency response function is gained from the estimation of the excitation force



and the response of the system [3]. Modal parameters consist of natural frequency, damping ratio and modes shapes which are obtained from the measured data [4].

Classical modal analysis or also known as experimental modal analysis (EMA) and operational modal analysis are the two types of the most widely used modal analysis method. The dissimilarities in force excitation are the biggest difference between experimental modal analysis and operational modal analysis. The force excitation for experimental modal analysis is gained from human activities and considered to be calculated. Meanwhile, the force excitation for operational modal analysis is gained from the natural surroundings or any mechanical activities which are also known as white noise [5]. The signal obtained might be interrupted by the ambient and the interference signals which would hide the useful data for the identification of modal parameter [6].

EMA has a limit as it is necessary to measure all the force excitation on the structure which is impracticable for operating structures [7]. The operational modal analysis was introduced to overcome EMA weakness because this analysis can be carried out under the operating conditions and depends only on the output response without required any input excitation [8]. However, the operational modal analysis also has drawback in term of modal parameter extraction. Without the force excitation, the mode shapes cannot be standardized precisely and would interrupt the mathematical process [9].

This paper focuses on the development of Wavelet-based filter to suppress ambient effect in vibration response measurement. Vibration responses measured from EMA procedure under ambient operating force is a superposition of the response from the artificially induced force and unidentified ambient forces. Therefore, the ambient vibration response needs to be filtered out to prevent error in transfer function calculation.

## 2. Theoretical background

### 2.1. Experimental Modal Analysis (EMA)

Experimental modal analysis (EMA) or also known as modal testing is one type of non-destructive testing used in the vibration system to identify the structural responses [10]. It has already been used for decades in determining the modal damping of the structure. It works based on the input-output modal identification which allows the identification of frequency response functions (FRFs) by referring to coherence functions [7]. Experimental modal analysis (EMA) technique is operated based on the impact test which involved the excitation of external forces onto the structure by using either hammer or shaker to determine the frequency response functions (FRFs) and estimate the mode shapes and modal damping of the system [11].

The structural vibration response towards the impact excitation obtained from the signal analysis is measured and transformed into frequency response functions (FRFs) by using Fast Fourier Transformation (FFT) method [10]. Frequency response function (FRF) is a basic principle of measurement for obtaining the mechanical structural dynamic characteristics of a structure [12]. It is also known as a transfer function and is denoted by the frequency domain [13]. The equation for the transfer function is obtained from the linear mechanical system. The equation for the transfer function [13] is represented by equation (1).

$$H(\omega) = \frac{X(\omega)}{F(\omega)} \quad (1)$$

where  $H(\omega)$  is a transfer function,  $X(\omega)$  is an output response and  $F(\omega)$  is an input force. The output response of the experimental modal analysis (EMA)  $X(\omega)$  becomes the linear superimposition for the induction forces in the operating system.

The estimated input force introduced by the artificial excitation,  $F$  would be added with all the omitted operating and ambient forces in the system. It would cause an error to the transfer function,  $X(\omega)$  as the only one induction force that is being introduced by the impact hammer is assumed to be the overall response of the system through the spectrum. The error is also influenced by the low

coherence function of the system [9]. The equation for the operating experimental modal analysis is given by the equation (2) below:

$$X(\omega) = [H1(\omega) * F1] + [H2(\omega) * F2] + [H3(\omega) * F3] + \dots \quad (2)$$

In this case, the response due unaccounted forces should be suppressed in order to minimise the error in transfer function calculation.

## 2.2. Wavelet Transform

Wavelets are described as a small wave that is used to prevent the deficiencies of the Fourier transform [14]. The mathematical formulation of the wavelets is used to restrict the data which consists of both time and frequency domain [15].

There are two types of wavelet transform analysis which is continuous wavelet transform (CWT) and discrete wavelet transform (DWT). Continuous wavelet transform (CWT) is applied to identify the multiple time series features. It works based on the conversion and extension of the mother wavelet,  $\psi(t)$  with the function of time,  $t$ . The continuous wavelet transform is represented [16] by the equation (3):

$$W(k, l) = \int_{-\infty}^{+\infty} x(t) * \psi_{k,l}(t) dt \quad (3)$$

where 
$$\psi_{k,l}(t) = \frac{1}{\sqrt{k}} * \psi * \left(\frac{t-l}{k}\right) \quad (4)$$

With  $k$  is the scaling and  $l$  is the translation.  $W(k, l)$  is the coefficient of the wavelet transform and  $\psi$  is the function of the mother wavelet.

Discrete wavelet transform is a new analysis method that is used to discretize the translation and scale of the continuous wavelet transform due to the data dismissal and the huge computational result [17]. The equation for the discrete wavelet transform is represented [16] by the equation (5).

$$\psi_{k,l}(t) = \frac{1}{\sqrt{2^j}} * \psi * \left(\frac{t-m \cdot 2^j}{2^j}\right) \quad (5)$$

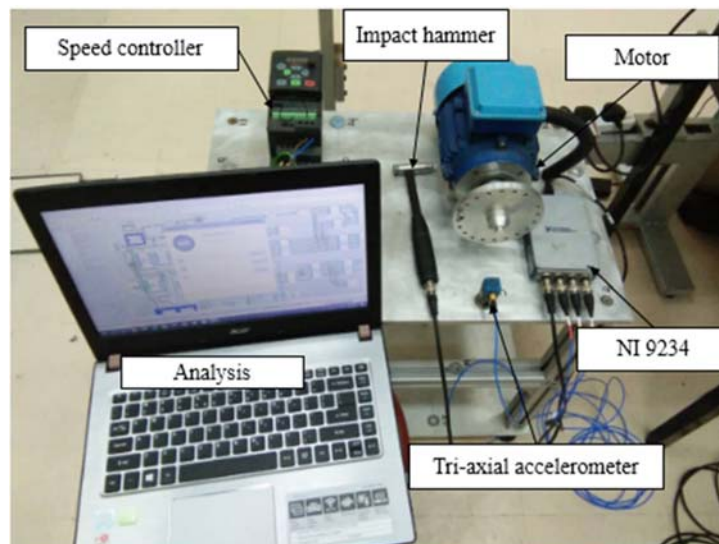
The discrete wavelet transform (DWT) depends on the recursive filter bank consists of a low-pass filter and a high-pass filter with down sampling by a factor of 2. For the inverse discrete wavelet transform, all the sub-band signals are integrated to form the reconstruction of the output signal with the up sampling instead of down sampling operator in forwarding discrete wavelet transform [16].

## 3. Experimental setup

In this study, vibration impact test was performed on a motor-driven structure in order to obtain its dynamic properties. The rig structure consists of a motor speed controller and a synchronous motor which are attached to the top platform of the rig structure. It has four pillars that are used to support the upper part of the rig structure to the lower part. The measurements were carried out with two different condition i.e. shut down condition and running condition. In running condition, the ambient force was induced from a disc attached on the motor and speed controller cooling fan. An impact hammer was used to induce the artificial impact force at a fix point and the vibration responses at each point were measured using tri-axial accelerometer. The frequency response function (FRF) obtained were recorded for the post processing purpose. The specification of the instruments is shown in table 1. The sampling frequency and block size is selected at 2048Hz and 4096 respectively. Figure 1 shows the tools arrangement for this experiment.

**Table 1.** List of instruments.

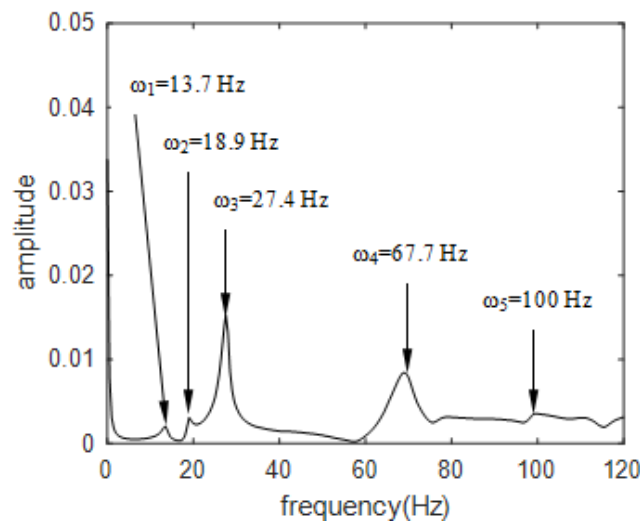
| Instruments   | Description  |
|---|--|
| NI USB Dynamic Signal Acquisition Module, Model NI-USB 9234 | Number of channel: 4<br>ADC resolution: 24 bits<br>Max Sampling Rate: 52KHz                            |
| PCB Impact Hammer, Model 086020                             | Sensitivity: 0.23 mv/N   |
| PCB Tri-Axial Accelerometer, Model 356B08                   | Sensitivity: 98.3 mv/g ( <i>x</i> -axis)<br>99.4 mv/g ( <i>y</i> -axis)<br>97.6 mv/g ( <i>z</i> -axis) |

**Figure 1.** Experimental setup for modal testing analysis.

## 4. Results and discussion

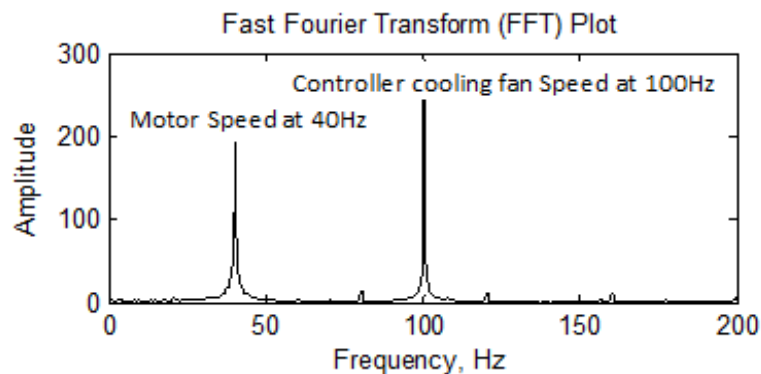
### 4.1. Bump test

From the experiment, input force and vibration response were measured in order to obtain the Frequency Response Function (FRF) through cross and auto correlation function. The FRF of the measurement under shut down condition will be used as based line data. Figure 2 shows the FRF plot under shut down condition.



**Figure 2.** FRF plot under shot down condition.

The process revealed natural frequency for the structure at 13.7Hz, 18.9Hz, 27.4Hz, 67.7Hz and 100Hz. For running condition, the motor speed was set at 40 Hz. In addition, another source of ambient from speed controller cooling fan was running simultaneously at the speed of 100 Hz. The frequency spectrum of the ambient response from that running equipment is shown in figure 3. The presence of high peak at correspondent excitation frequency will affect the FRF calculation for the running condition. Therefore, those frequency characteristics need to suppress from measured response in order to minimise the effect of ambient excitation forces.

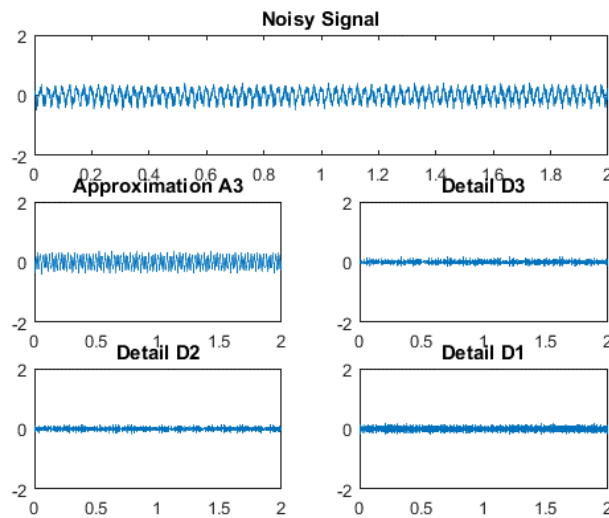


**Figure 3.** Frequency spectrum of the structure under ambient operating force.

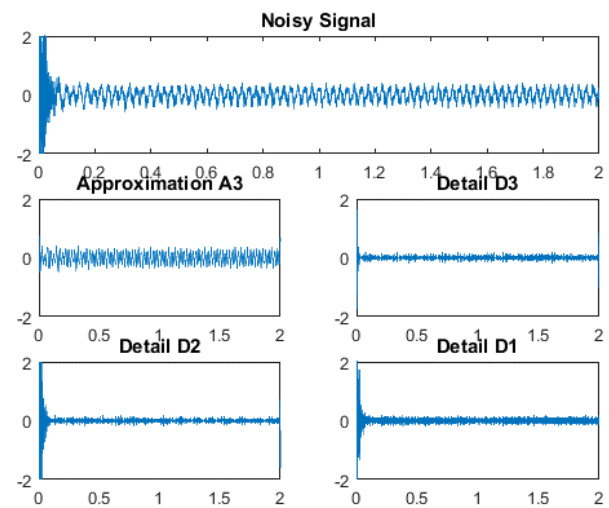
#### 4.2. Wavelet-based Filter

In this study, a wavelet-based filter was utilised to filter out the ambient from impact test procedure. Two input signals were used for filtering signal which is ambient response and impact response under running condition. Both signals were decomposed into three level of decomposition using Discrete Wavelet Transform (DWT) as shown in Figures 4 and 5. The discrete DWT is modified by combining the wavelet transform with spectral subtraction. Instead of using a thresholding method to filter the noise in each level of decomposition, the spectral subtraction is applied at every level of decomposition. The

value of thresholding is fixed where it will cut the noise according to the input value and might cut some of the useful data from the signal. Meanwhile, the spectral subtraction eliminates the noise by subtracting the coefficient level of total response with the ambient and then divided it with the coefficient level of total response for every level.



**Figure 4.** Wavelet decomposition for ambient response.



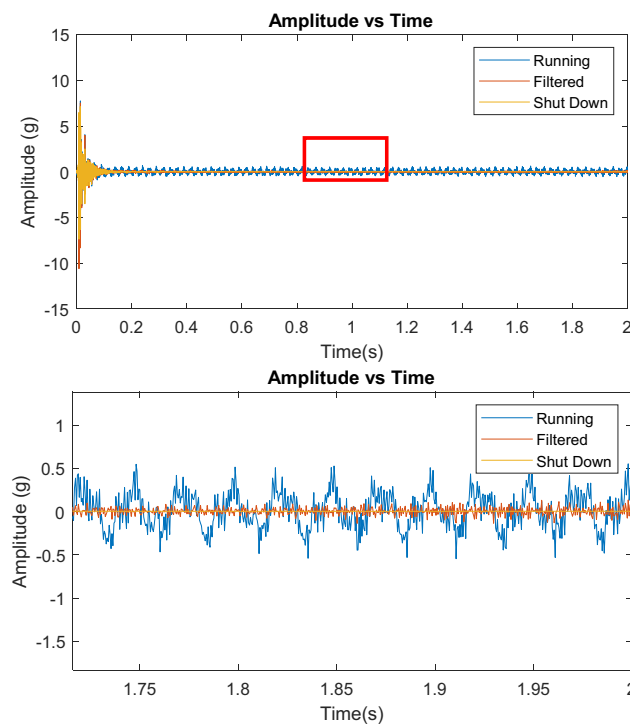
**Figure 5.** Wavelet decomposition for impact response under running condition.

By using the discrete wavelet transform, the signal is divided into three levels of decomposition. For each level, the output is having a down sampling by a factor of two. The output for the filter consists of the approximation coefficient and details coefficient. The approximation coefficient consists of low pass filters whereas the details coefficient consists of high pass filters. According to the principle of the

discrete wavelet transform states, only the details coefficient is let to be passed through whereas the approximation coefficient is needed to be down sampling once again by a factor of two. The down sampling process is repeated until the desired output is obtained.

After filtering the signal into three levels of decomposition, the spectral subtraction is applied to each level of decomposition. The spectral subtraction utilised the frequency information for every decomposed signal to generate signal to noise ratio. Signal to noise ratio is referred to the ratio of magnitude for clean signal over noisy signal, whereas magnitude of clean signal is the output of subtraction between noisy and ambient magnitude. Next, the spectrum was then inversed into time domain to obtain the clean signals at every decomposition level.

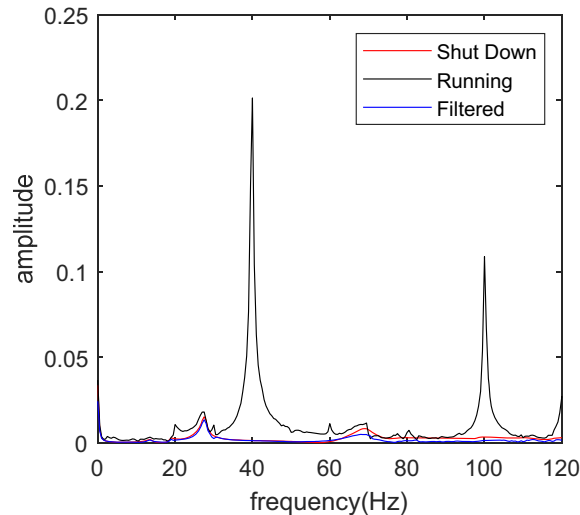
Finally, all the decompose signals is reconstructed using Inverse Discrete Wavelet Transform (IDWT) to produce a clean signal. The time domain plots for impact responses under shut-down condition, running and after filtered are overlaid in figure 6. From the time domain data, it is clearly seen that the ambient is completely being filtered out by the modified discrete wavelet transform (DWT). The proposed method has completely eliminated the ambient without affecting any useful data from the signal which is very important to be preserved in order to find the modal parameter of the structure.



**Figure 6.** Time domain plot for impact response.

Based on filtering process, the clean impact response spectrum is cross and autocorrelation with input force from impact hammer to obtain the transfer function. In this case, the transfer function of the filtered signal will be compared with the condition when the system is running and shut down. The Frequency Response Function (FRF) plot in figure 7 shows at the operating frequencies 40 Hz and 100 Hz were successfully suppressed. The filtering process using wavelet-based filter suppressed the ambient magnitude contained in frequency spectrum to minimize the effect of ambient and restored the main features as found in baseline data.





**Figure 7.** Comparison FRF plot between shut down, running and filtered signals.

## 5. Conclusions

This paper discusses on the study of an ambient suppressing technique using Spectrum Deviation filter (SDF). This filtering method utilized frequency spectrum coefficient from FFT algorithm to produce the filter response. The filter response is determined from the inverse component of the residual frequency spectrum, SDR. The filtering process was performed based on normalization of measured vibration spectrum with the filter response which suppressed the ambient effect that contain in the measured vibration response. As a result, a new filtered vibration response was obtained for the purpose of transfer function calculation in EMA.

In this case, a set of data from EMA on a motor driven structure were used for filtering process. The data that taken under operating condition were filtered using SDF and the obtained transfer functions were compared with the shutdown condition. The transfer function calculation from measurement under ambient operating force shows the frequency components at operating speed were affected. However, post filtering transfer function shows a much closed to the signal measured under shutdown condition especially with the embedded of phase reallocation algorithm.

The findings indicate that SDF method can be used to develop an effective filtering algorithm for EMA procedure under ambient operating force. With the ability to suppress the ambient effect, the developed algorithm in this study is recommended as an alternative method to perform modal analysis on a structure without shutting down the machine.

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