Analysis of Horizontal to Vertical Spectral Ratio (HVSR) Curve Results from Processing using Interpolated Finite Impulse Response (IFIR) Filter

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Abstract. Microtremor is recorded with a device that is very sensitive to subsurface soil vibrations, that unwanted noise frequency waves are often also included. For this reason, processing needs to be done using filters that can attenuate the noise. In the previous research, signal decomposition was performed using the Interpolated Finite Impulse Response (IFIR) filter and resulted attenuation at the desired frequency value. Using the MATLAB program, microtremor data are processed with IFIR filtering, smoothing, calculation of: Horizontal to Vertical Spectral Ratio (H/V) curve, natural frequency (f0) and standard deviation (σ). The same process was carried out using Butterworth, Gaussian, and Cosine filters as a comparison with the Geopsy program. As a result, the amplitude characteristics obtained can provide a value of f0 < 2.5 Hz. The value of f0 obtained using IFIR filter is also stable, proven by the standard deviation ranging from σ = 0.009 - 0.83 Hz, with an average of σ = 0.132 Hz. In conclusion, the IFIR filter can provide a well-attenuated H/V curve according to the specified cutoff frequency, which was 2 Hz. The IFIR filter is also considered capable of being applied to the HVSR method Microtremor data. Lowpass IFIR filter can attenuate high-frequency noise in microtremor data.

1. Introduction

Microtremor is a natural harmonic vibration of the soil which is very small and occurs continuously, trapped in the surface sediment layer, then reflected by the presence of reflected fields that have a fixed frequency value, due to micro-vibrations below the surface of the ground, and human activities [1]. The natural frequency value from the Horizontal to Vertical Spectral Ratio (HVSR) method will represent rock characteristics that dominate in the measurement area, such as sediment thickness [2–4]. The high sensitivity of the microtremor to micro-vibrations will result in a lot of recorded noise. Therefore, a method that can eliminate the noise, namely filtering, is mandatory. One filter that can be used is the Interpolated Finite Impulse Response filter because this filter is able to attenuate unwanted frequency content [5,6].

The previous research was done to apply the Interpolated Finite Impulse Response (IFIR) filter to gravity data in the Java Island Region. One of the IFIR filter characteristics is that it has a narrow transition band. By so, the carried-out filtering process yielded more precise cutting of frequency component values. The research uses the lowpass type filter to attenuate higher frequency component. As a result, low frequency spectral was generated with high-frequency component being well attenuated [7,8]

The purpose of this study is to determine the characteristics of the HVSR curve from processing using IFIR lowpass filter and the effect of high-frequency noise after being given an IFIR lowpass filter. The scope of problem in this research is that for the filter design and signal processing with IFIR filter uses MATLAB 2018b program, and the signal processing with built-in conventional filters as a comparator uses Geopsy software.
2. Theory

2.1. Microtremor Method

Microtremor is a very small and continuous ground vibration that originates from a variety of vibrations such as traffic, wind, human activities, and others. Microtremor can also be interpreted as a natural harmonic vibration of the soil that occurs continuously, trapped in the surface sediment layer, reflected by the presence of reflected fields that have a fixed frequency value, caused by micro-vibrations below the surface of the ground and other natural activities [1]. Microtremor is applied to determine the dynamic characteristics (natural frequency and amplification factor) of the soil layers [9]. In practice, microtremor measurements are used to observe the characteristics of soil dynamics that can be viewed from seismic waves. Some physical parameters that can be seen are seismic wave velocity, amplitude variation, frequency, and wave period [9]. The period length of microtremor is 1.6 - 2 seconds or more. Natural waves from microtremors vary, depending on the conditions of the region [10]. The basic principle of applying microtremor is to study subsurface effects, based on the principle that the microtremor moves as a subsurface wave and is amplified in periods that are synchronized with natural periods in the subsoil. Simultaneous selection of resonance increases the frequency component. While the microtremor period tends to reflect subsurface formation, the period length is always related to the depth of the formation [10].

2.1.1. Horizontal to Vertical Spectral Ratio (HVSR). It is a method based on the assumption that the ratio of horizontal and vertical spectra of surface vibrations is a function of displacement [9]. In assessing the dynamic characteristics of surface soil layers causing local site effects during an earthquake, this method is very economical and effective. Most of the microtremor energy is sourced from Rayleigh Waves, and the amplification of site effects is due to the presence of soft soil layers that occupy half the basins of the bedrock. In this condition there are four components of ground motion involved, namely the horizontal and vertical movement components in the bedrock and the horizontal and vertical motion components on the surface [11].

2.1.2. Natural Frequency. Natural frequency represents the number of waves that occur at one time. Natural frequency is a frequency that often appears so that it is recognized as the frequency value of the rock layers in the region so that the frequency value can indicate the type and characteristics of rocks [1]. According to Kanai, the natural frequency value of microtremor measurements can provide information about the types of soil classified according to the following Table [12]:

| Classification Type | Class | Frequency (Hz) | Kanai Classification | Description |
|---------------------|-------|----------------|----------------------|-------------|
| IV                  | I     | 6.667 – 20     | Tertiary or older rocks consist of hard sandy rocks, gravel, etc. | The thickness of surface sediments is very thin, dominated by hard rock. |
| IV                  | II    | 10 – 4         | Alluvial rocks, with a depth of 5 m. Consists of Sandy - Gravel, Sandy Hard Clay, Loam etc. | The thickness of surface sediments falls into the medium category of 5-10 meters. |
| III                 | III   | 2.5 – 4        | Alluvial rocks, with thickness> 5m. Consists of sandy-gravel, sandy hard clay, loam, etc. | The thickness of surface sediments falls into the thick category, around 10-30 meters. |
| II and I            | IV    | < 2.5          | Alluvial rocks, which are formed from delta, topsoil, mud sedimentation with a depth of 30 m or more | The thickness of the surface sediment is very thick. |
2.2 Interpolated Finite Impulse Response

FIR filters with sharp ranges have the disadvantages of higher-order with the same level of functionality compared to other filters, as well as the large computational capacity [5]. To reduce the shortcomings of the FIR filter, a FIR filter design was carried out with an interpolation technique, Interpolated Finite Impulse Response (IFIR). In figure 1 an operator of the initial FIR Filter $G(e^{j\Omega})$ is then made in a more expanded shape than the desired filter as shown in figure 1 (b). Stretch factor ($L$) is the ratio between the range that is increased in the prototype filter to the desired filter. The greater the value of $L$, then the length of the passband will be wider, and the order of the filter will be smaller by a factor of $L$. The prototype filter is then masked by 'interpolator' as much as $L$ as shown in figure 1 (c) so that it forms a filter $G(e^{jL\Omega})$, shown in figure 1 (d). Although interpolation is done, this does not change the sample rate in the subfilter. The next step is to refilter the sub-filter with $I(z)$ to patent the unwanted repetition [6].

![Figure 1. Magnitude response of IFIR filter design: (A) Filter prototype; (B) Filter with L factor expansion; (C) Sub filter Interpolator for Masking; (D) IFIR result [6]](image)

### 3. Methodology

This study uses 43 measurement data points from microtremor study at Sedati, Sidoarjo, East Java [13]. Flowchart on methodology phases is described on figure 2. First is the preparation phase, this stage includes the collection of microtremor data needed for research.

| Filter Specification       | Magnitude |
|----------------------------|-----------|
| Stopband attenuation       | -30 dB    |
| Passband edge frequency    | $f_c$     |
| Stopband edge frequency    | $f_c+1$   |

The next phase is the processing stage, starting from the preparation of time series data by inputting into MATLAB and Geopsy software. Then, data are compiled into a time series diagram using the functions that have been available for time analysis. From this phase we can already determine the amount of noise in the data qualitatively. Next the data are filtered using Geopsy built-in lowpass filters which are Butterworth, Gaussian, and Cosine. Filtering is performed on the initial data using filter operators with determined cutoff frequency ($f_c$) value. The cutoff value used in Geopsy is then also used as the input variable for the filter function in MATLAB. The goal is to eliminate the frequency component above the cutoff frequency ($f_c$) value. In this study, MATLAB software with the Digital Signal Processing Toolbox module is used to design the IFIR lowpass filter. The filter parameters used are listed in table 2.
The last phase is the analysis. The results of filtered data are then converted into the frequency domain again using the Fast Fourier Transform (FFT) algorithm to be compared with the initial data. The filter is said to be appropriate if the frequency component amplitude values match the specifications of the filter. Then, the natural frequency value will be yielded. This process is repeated for each measurement point and then recorded in Microsoft Excel. The results obtained from processing using MATLAB and Geopsy software are then analyzed and compared.

Figure 2. Research flowchart
4. Result

Figure 3. (A) IFIR impulse response amplitude curve, in the sample domain (second). (B) The amplitude curve of the IFIR operator in the frequency domain ($\pi$ rad/sample). (C) Amplitude curve of the IFIR operator in the range 0 - 0.08 $\pi$ rad/sample.

In figure 3 (a), the impulse response form of the lowpass IFIR filter operator is shown. In accordance with the literature review, that IFIR is a FIR interpolation which impulse response is in the form of a cardinal sinus. In figure 3 (b), the lowpass IFIR filter operator meets the specified specifications. The frequency scale in the figure is expressed in Normalized Frequency in units $\pi$ rad/sample. There is a Gibbs Effect in the stopband range from 0.016 $\pi$ rad/sample (2 Hz) to Nyquist Frequency 1 $\pi$ rad/sample (125 Hz). To analyze the spectral results of microtremor filtering data that only reach a range of 0.08 $\pi$ rad/sample (10 Hz), then in figure 3 (c) the amplitude window operator filter IFIR is shown. In this figure, the frequency scale is also expressed in Normalized Frequency with units $\pi$ rad/sample.

Because the IFIR is a combination of several intercepted FIR operators, the IFIR operator obtained has an amplitude shape that resembles the FIR operator that is repeated along the frequency. For example, the amplitude form from 0.16 - 0.35 $\pi$ rad/sample has the same amplitude shape in the range...
0.35 - 0.52 \pi \text{ rad/sample}. In the stopband range, we found that the amplitude is affected by the Gibbs Effect which has a magnitude of -120 dB. However, in the other range, the amplitude is found from -240 dB to -300 dB. This can affect the shape of the filter signal amplitude. The signal frequency range multiplied by the IFIR operator in the filter frequency range affected by the Gibbs Effect, will have a value that is momentarily greater than some of the samples afterwards.

In this filter, the Gibbs Effect will not affect signal, because the range of filtered frequency ranges does not reach the range where the Gibbs Effect occurs. That is because in the IFIR filter operator created this time, the maximum range of signals used does not reach the length of one FIR interpolated in the IFIR.

Microtremor data that is time series is then carried out transformation into the frequency domain using the Fast Fourier Transform algorithm. The changed data is then filtered by multiplication in the frequency domain. After filtering, data needs to be smoothed to ease spectrum analysis. Smoothing is done by giving a Tukey window with a tapering length of 5%.

**Figure 4.** (a) Initial spectrum (b) Tukey Window. (c) Result of windowing and filtering

Figure 4 shows an example of the spectrum of vertical components at point 21 given smoothing using a Tukey window. The initial spectrum in figure 4 (a) shows the shape of the initial spectrum, which is still relatively difficult to analyze. Figure 4 (b) shows the amplitude of the Tukey window in the frequency domain. The initial data spectrum is multiplied by the Tukey window, resulting in a relatively smoother spectrum, as shown in Figure 4 (c).

Then the Horizontal per Vertical (H/V) value is generated using the Average Squared method. The H/V spectrum results are then given smoothing again with the Konno-Ohmachi algorithm with a smoothing constant of 20, and a window sample of 40% as shown in figure 5.
The generated H/V data for each iteration is presented in one vector with length \( n \). To get the value of Natural Frequency \( (f_0) \) from an iteration, a calculation is performed on each \( i \)-th sample using the following formula:

\[
\sum_{i=1}^{n} \text{amplitude}(i) \times \frac{1}{\sum_{i=1}^{n}}
\]

Obtained the value of \( f_0 \) on one iteration, then the iteration is repeated using the looping function for as many windows used. In this processing, a window of 200 seconds is used on microtremor measurement data with a duration of 30 minutes. Hence, we get 9 windows each with a length of 200 seconds. The value of \( f_0 \) is obtained from all iterations, then the average value and standard deviation are calculated. This value is used as the \( f_0 \) value of one data using the IFIR filter in MATLAB software. This processing is also carried out using Geopsy software. With the same cutoff filter, windowing, and smoothing specifications, the processing is done using mentioned Geopsy filters to get the value \( f_0 \). Table 3 is the result of the \( f_0 \) values from filtering using IFIR, Butterworth, Gaussian, and Cosine filters.

| Point | \( f_0 \) IFIR | \( f_0 \) Butterworth | \( f_0 \) Gaussian | \( f_0 \) Cosine |
|-------|----------------|-----------------------|-------------------|----------------|
| 1     | 1.2439         | 3.14715               | 2.14775           | 0.637401       |
| 2     | 1.8287         | 0.894819              | 0.898353          | 0.898353       |
| 3     | 0.9935         | 0.974212              | 0.974212          | 0.974212       |
| 4     | 1.0636         | 5.42326               | 1.19765           | 1.19765        |
| 5     | 2.1818         | 1.87                  | 2.20772           | 2.20596        |
| 6     | 1.4672         | 2.21479               | 2.44463           | 2.37933        |
| 7     | 1.5057         | 1.99327               | 2.38548           | 2.54039        |
| 8     | 1.101          | 2.06416               | 2.28392           | 2.30827        |
| 9     | 1.1807         | 1.83082               | 1.96059           | 1.94009        |
| 10    | 1.0476         | 2.22573               | 2.30838           | 2.32492        |
| 11    | 2.9595         | 2.17649               | 2.17785           | 2.21225        |
| 12    | 1.1448         | 2.0666                | 2.28229           | 2.27432        |
| 13    | 1.2117         | 2.06354               | 2.20469           | 2.166          |
| 14    | 1.0424         | 0.682055              | 0.682055          | 0.682055       |
| 15    | 0.6909         | 2.76131               | 2.32385           | 2.27192        |
| 16    | 1.0668         | 1.73108               | 1.80182           | 1.79454        |
Overall, the value of $f_0$ is almost entirely already at the specified cutoff value, which is 2 Hz. In processing using IFIR, the graph shows that the $f_0$ value of the IFIR has a smaller value trend when compared to processing Butterworth, Gaussian, and Cosine filters. Even so, an increase in the value of $f_0$ at point 11 is greater than the other three filters. In processing using Butterworth, the graph shows that the value of $f_0$ has a trend of relatively greater value of the other three filters. Even at points 4, 27 and 28 there are values that exceed the cutoff frequency = 2 Hz. The results of processing Gaussian and Cosine filters show relatively similar results. In the second processing, the graph shows that the value of $f_0$ has a trend value that is in accordance with the cutoff frequency specification. However, there are several points with $f_0$ values higher than the cutoff frequency.

As a measure of the confidence level of $f_0$ values, we calculate the standard deviation ($\sigma$) of the processing results from each filter. In figure 7, the results of the calculation of the standard deviation of the four filters are shown. Overall, the lowest standard deviation value when calculating the average is from the Butterworth filter with an average standard deviation ($\bar{\sigma}$) = 0.121. The highest average standard deviation is generated by Cosine filters ($\bar{\sigma}$ = 0.149) and Gaussian ($\sigma$ = 0.144). The average standard deviation of the IFIR filter is $\bar{\sigma}$ = 0.132. In the IFIR filter processing, there are several processing points that have relatively higher standard deviation values than the other three filters, namely at points 5, 18, 23, 41, 42, and 43.

| Filter | Average Standard Deviation | | | | |
|--------|-----------------------------|-----------------------------|-----------------------------|-----------------------------|-----------------------------|
| Butterworth | 0.121 | | | | |
| Gaussian | 0.144 | | | | |
| Cosine | 0.149 | | | | |
| IFIR | 0.132 | | | | |

| Point | $f_0$ | Standard Deviation | Standard Deviation | Standard Deviation | Standard Deviation |
|-------|-------|--------------------|--------------------|--------------------|--------------------|
| 17    | 0.9729 | 0.641222 | 0.641222 | 0.641222 | 0.641222 |
| 18    | 1.1819 | 0.961362 | 0.956226 | 0.956226 | 0.956226 |
| 19    | 0.8528 | 0.917109 | 0.912314 | 0.912314 | 0.912314 |
| 20    | 1.0428 | 1.222122 | 1.222122 | 1.222122 | 1.222122 |
| 21    | 0.9335 | 0.892648 | 0.892648 | 0.892648 | 0.892648 |
| 22    | 0.8532 | 0.671538 | 0.671538 | 0.671538 | 0.671538 |
| 23    | 1.1179 | 0.797155 | 0.797155 | 0.797155 | 0.797155 |
| 24    | 0.8435 | 0.61056 | 0.61065 | 0.61056 | 0.61056 |
| 25    | 0.8451 | 0.631126 | 0.631126 | 0.631126 | 0.631126 |
| 26    | 0.8437 | 0.612778 | 0.612778 | 0.612778 | 0.612778 |
| 27    | 1.0305 | 3.31554 | 2.28 | 2.25164 | 2.25164 |
| 28    | 1.4155 | 11.6576 | 2.26844 | 2.30691 | 2.30691 |
| 29    | 1.5398 | 1.68114 | 1.85976 | 1.84895 | 1.84895 |
| 30    | 1.0139 | 1.07425 | 1.07425 | 1.07425 | 1.07425 |
| 31    | 0.9671 | 0.970762 | 0.970762 | 0.970762 | 0.970762 |
| 32    | 0.8103 | 0.613069 | 0.613069 | 0.613069 | 0.613069 |
| 33    | 0.8609 | 0.867124 | 0.867124 | 0.867124 | 0.867124 |
| 34    | 0.8606 | 0.671226 | 0.671226 | 0.671226 | 0.671226 |
| 35    | 0.8064 | 0.616409 | 0.616409 | 0.616409 | 0.616409 |
| 36    | 0.9822 | 0.943501 | 0.943501 | 0.943501 | 0.943501 |
| 37    | 1.0064 | 0.89739 | 0.89739 | 0.89739 | 0.89739 |
| 38    | 1.0375 | 0.960575 | 0.960575 | 0.960575 | 0.960575 |
| 39    | 0.9438 | 1.02505 | 1.02505 | 1.02505 | 1.02505 |
| 40    | 0.8745 | 0.814801 | 0.814801 | 0.814801 | 0.814801 |
| 41    | 1.7559 | 0.659044 | 0.659044 | 0.659044 | 0.659044 |
| 42    | 1.5021 | 0.606384 | 0.606384 | 0.606384 | 0.606384 |
| 43    | 1.2654 | 0.812483 | 0.812483 | 0.812483 | 0.812483 |
After processing using MATLAB in accordance with the parameters, the H/V curve can be analyzed with the filter specifications used. For example, an appropriate H/V result is obtained at processing point 21. In this case, point 21 is rated as a good quality point. It can be seen qualitatively in Figure 8, that the filtered H/V curve shows the peak amplitude below the cutoff frequency = 2 Hz. Above the value of 2 Hz, amplitude attenuation has occurred. The resulting $f_0$ value is also below the cutoff frequency of 0.9335 Hz, with a relatively small standard deviation of 0.0179 Hz.
Figure 8. Filtering using IFIR on Point 21

A sample of H/V results that are less appropriate is obtained at processing point 28. In this case, point 28 is rated as a point of poor quality. It can be seen qualitatively in Figure 9, that the H/V curve of the filtering results shows the peak amplitude is below the cutoff frequency = 2 Hz. However, the resulting $f_0$ value is not at the peak of the curve's amplitude, but rather is at a range greater than the peak of its amplitude. This is because the amplitude value that coincides with the range of the transition band on the IFIR filter has a high value. The standard deviation before processing is 0.2794 Hz and after processing 0.0574 Hz. Filtering gives a smaller standard deviation from the initial data.

Figure 9. Filtering using IFIR on Point 28
At point 21, the value of \( f_0 = 0.892 \) Hz was obtained, while processing using IFIR yielded \( f_0 = 0.933 \) Hz. The value of \( f_0 \) obtained has a difference of about 0.1 Hz, with the IFIR having a greater value. However, the Butterworth filter has a greater standard deviation. The Butterworth filter produces a standard deviation \( = 0.09 \) Hz, while the IFIR filter produces a standard deviation \( = 0.01 \) Hz.

At point 28, the value of \( f_0 = 11.657 \) Hz, while processing using IFIR obtained \( f_0 = 1.415 \) Hz. The value of \( f_0 \) obtained has a difference of around 10.2 Hz, with the IFIR having a smaller value and below the cutoff frequency. The Butterworth filter produces a standard deviation of \( 0.614 \) Hz, while the IFIR filter produces a standard deviation \( = 0.057 \) Hz.

From both sample points 21 and unfavourable points 28, the IFIR filter was judged to be better in producing an H/V curve, with a smaller value of \( f_0 \) and standard deviation than the Butterworth filter processing.

![Figure 10. Filtering using Butterworth on Point 21 and Point 28](image-url)
At point 21, the value of $f_0 = 0.892$ Hz was obtained, while processing using IFIR obtained $f_0 = 0.933$ Hz. The value of $f_0$ obtained has a difference of about 0.1 Hz, with the IFIR having a greater value. However, the Cosine filter has a greater standard deviation. The Cosine filter produces a standard deviation = 0.09 Hz, while the IFIR filter produces a standard deviation = 0.01 Hz. At point 28, the value of $f_0 = 2.306$ Hz is obtained, while the processing using IFIR obtained $f_0 = 1.415$ Hz. The value of $f_0$ obtained has a difference of about 0.9 Hz, with the IFIR having a smaller value and below the cutoff frequency. The Cosine filter produces a standard deviation of 0.233 Hz, while the IFIR filter produces a standard deviation = 0.057 Hz.

From both sample points (21) and unfavourable points (28), the IFIR filter is considered better in producing an H/V curve, with a value of $f_0$ or standard deviation that is smaller than the Cosine filter processing.
5. Conclusion
In this research, we have demonstrated the processing of HVSR data carried out using Interpolated Finite Impulse Response (IFIR) lowpass filter. Research is done by comparing the resulting HVSR curve yields using IFIR lowpass filter with HVSR curve yields using conventional lowpass filters (Butterworth, Gaussian, and Cosine). The HVSR curve yielded by the IFIR filter can be well attenuated according to the specified cutoff frequency, which is 2 Hz. The amplitude characteristic given by the filtering can also give a valid f0 yield, proven by the value of f0 is in accordance with the type of soil (< 2.5 Hz) the small range of standard deviation (σ = 0.09 – 0.83 Hz), and the small value of mean standard deviation (√σ = 0.132). The smaller value of standard deviation range and mean standard deviation from IFIR filter compared with conventional filters implies that processing of HVSR data using IFIR lowpass filter in this study is more precise.

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