0931

USE OF SYNCHRONOUS NOISE AS TEST SIGNAL FOR EVALUATION OF STRONG MOTION DATA PROCESSING SCHEMES

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SUMMARY

A synchronous noise is a broad band time series having absolutely flat power spectrum and thus it is a much stronger version of white noise. In this paper, method to generate a synchronous noise and its use in evaluation of strong motion data processing schemes is presented. This time series is very useful for determining and evaluating the transfer function or frequency response of any mathematical model or process. Various parts of four different strong motion data processing schemes have been evaluated by determining the transfer function using synchronous noise as input. These results show that use of different types of filter for band pass operation give similar frequency response characteristics. However, linear interpolation performed in some of these schemes, corrupts the data in the entire frequency band. This work also shows that in case the original sampling rate is required to be increased then band limited interpolation should be used.

INTRODUCTION

The process of obtaining corrected accelerogram involves band pass filtering, instrument correction and interpolation and sometimes decimation. Several authors have suggested different schemes to perform these steps. Lee and Trifunac [8] have worked in time domain used Ormsby filter for band pass filter, second order central difference operation for instrument correction, interpolation done linearly and decimation through dropping of samples. Their scheme is known as Caltech scheme and is still used world wide as a standard correction scheme. Erdik and Kubin [2] also worked in time domain, used Ormsby filter for low pass operation, Butterworth filter for high pass operation (on velocity and displacement sequences) and linear interpolation. Khemici and Chiang [4] worked in frequency domain, used half cosine tapered filter with unit gain in pass band and zero gain in stop band. Authors of this paper have worked in frequency domain and have used $|H(j\omega)|$**2 of Butterworth filter for band pass filtering and interpolation through a method called as ‘band limited interpolation’ which maintains the frequency content of original sequence [6].

The accuracy and effect of these steps of the processing have often been questioned and therefore a need has always been felt to evaluate the correction schemes. Brady and Mork [1] has suggested use of synthetic accelerograms for testing various procedures. Accelerograms generated by them for this purpose had the appearance of recorded accelerograms. Also integrals of generated accelerograms approach zero after some time which implies that the signal was basically meant to test the accuracy of velocity and displacement histories obtained through different schemes. These accelerograms are not suitable to determine the frequency response of various steps of the scheme as well as entire scheme. Khemici and Chiang [4], while deriving their processing method, used impulse signal as input to the Caltech scheme and determined the impulse response, which is also the frequency response of the scheme. However, the data sequence of an impulse signal comprise of only one nonzero sample and all remaining zero samples. Thus, this type of signal is not useful to test the efficacy of interpolation and decimation. Also, the process of band pass filtering can not be evaluated as most of the input sequence comprises of zeros.

A broad band time series, which looks like random noise but has an absolutely flat power spectrum is known as synchronous noise (Harris [3]). A synchronous noise is a much stronger version of white noise. In the white noise, expected values of Fourier magnitude are identical which means Fourier magnitudes are approximately

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and not exactly equal as in the case of synchronous noise. In this paper, it is proposed that synchronous noise be used as test signal to evaluate various processing schemes. For evaluation of schemes, determination of their frequency response characteristics is the most vital and perhaps there can be no better method than using synchronous noise for this purpose. Although in this work, this signal has been used to evaluate and compare strong motion data processing schemes but this signal can also be effectively used to determine transfer function or frequency response of any other mathematical model or process.

It may be mentioned here that it is not essential that the test signal should look like a recorded accelerogram for determining the frequency response characteristics of a process. Also, authors feel that problems in obtaining correct velocity and displacement sequence are due to poor signal to noise ratio of the raw data at low frequencies as well as due to unknown initial conditions (for records of analog accelerographs) and is not caused by processing schemes. In fact, authors strongly feel that velocity and displacement histories obtained from accelerograms (particularly records of analog accelerographs) should be used with great caution as these can be substantially nonconservative.

SYNCHRONOUS NOISE

To generate synchronous noise, a constant is loaded into an array corresponding to nonzero spectral bins of an inverse discrete Fourier transform (IDFT). The IDFT of this data set will be a sequence which will be Drichlet kernel having high crest factor (ratio of peak to rms value). To reduce the crest factor, phase of the spectral terms is uniformly randomised. This requires use of random number generator to get numbers between -1 and 1. A random number is picked which is taken as areal part of the IDFT array and it's corresponding imaginary part is calculated such that a magnitude is a constant number (say 1). Similarly other pairs of real and imaginary parts of IDFT arrays are constructed such that magnitude of each pair is constant. Thus the array comprises of constant magnitude and random phase of each pair. IDFT of this data set yields synchronous noise which has an approximate Gaussian density function and a crest factor of about 3. In stead of random phase, if the phase is controlled by the following equation then a crest factor of about $\sqrt{2}$ can be obtained [3].

$$q(k) = q(0) + \left(\frac{p}{N}\right)k^2 \text{ , k= -N/2+1,.......,-1,0,1,........, +N/2}$$

where N is total number of sample points, $q(k)$ is the phase of k^{th} sample and $q(0)$ is an arbitrary phase factor.

However, in this work random phase and FFT algorithm for IDFT has been used to get the synchronous noise. Step by step method to generate synchronous noise of 1024 samples is as follows and a typical synchronous noise is shown in Fig. 1.

1. Pick a random number between –1 and 1 as real part of IFFT array.

2. Find its imaginary part = SQRT(1-real part **2)

3. Pick another random number and generate 513 such pairs corresponding to first 513 bin frequencies (Nyquist frequency).

4. For bin numbers 514 to 1024, real part are found by taking mirror image of real part of the set upto Nyquist frequency.

5. For bin numbers 514 to 1024, imaginary parts are found by taking negative of mirror image of imaginary parts of the set upto Nyquist frequency.

6. Inverse FFT is then performed on these 1024 pairs of real and imaginary parts, which yield the desired synchronous noise.

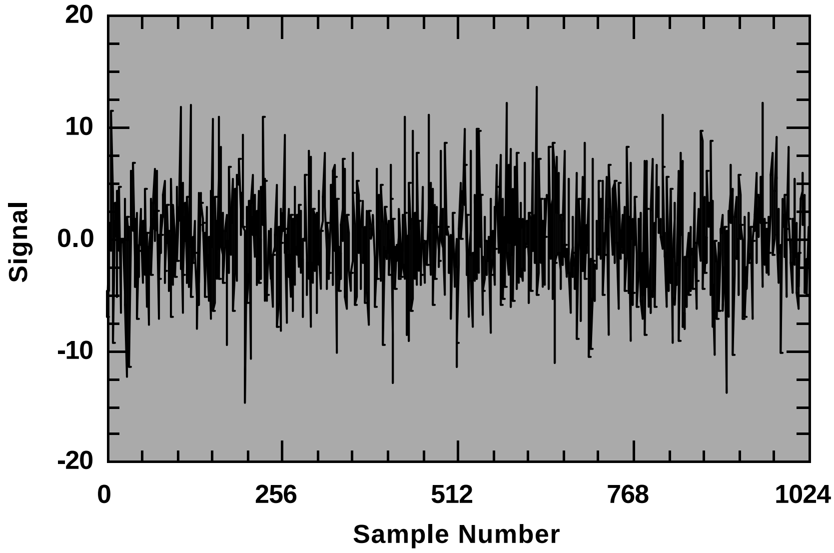

Fig.1 A Synchronous Noise of 1024 Samples

INSTRUMENT CORRECTION

A synchronous noise with 2048 data points assumed to be at 200 SPS is generated. Instrument correction of this signal is performed in time domain (as per Caltech scheme [8] and also the scheme of Erdik and Kubin [2]) assuming natural frequency of accelerometer as 20 Hz and damping to be 60% of critical. Similarly instrument correction of this synchronous noise is performed in frequency domain (as per scheme of Khemici and Chiang [4] and scheme proposed by authors [6]) for the same specifications of accelerometer. DFT of the instrument corrected sequence by the two methods are determined and their Fourier magnitudes (which are the frequency response of the process of instrument correction) are plotted one over the other as shown in Fig. 2. The plot shows that frequency domain instrument correction matches exactly with the ideal instrument correction process. Whereas time domain correction process, using second order central difference scheme, drops down at higher frequencies in comparison to ideal case. Thus, instrument correction process performed in frequency domain is clearly superior to time domain particularly for frequencies greater than 1/10 of the sampling frequency.

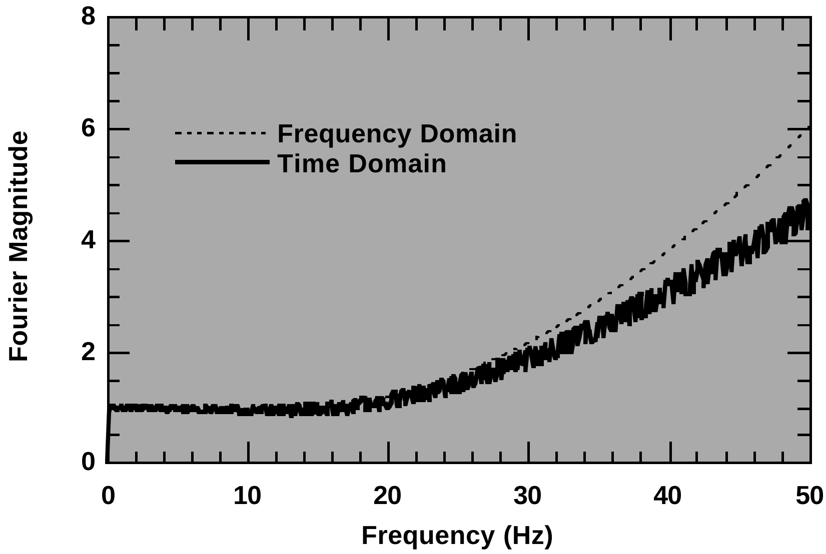

Fig.2 Frequency Response of Instrument Correction in Time and Frequency Domain

LOW PASS FILTER

Similarly, performance of low pass filter of different schemes are studied by using the synchronous noise of 2048 samples assumed at 200 SPS as input. The Caltech scheme and Erdik and Kubin scheme use Ormsby filter whereas the scheme of Khemici and Chiang uses half cosine-tapered filter and scheme proposed by authors uses Butterworth filter. A cut-off frequency of 25 Hz with a roll off of 2 Hz is taken and convolution is performed in time domain for Ormsby filter and in frequency domain for half cosine tapered filter as well as Butterworth filter. The low passed sequence for all the three filters for synchronous noise input is determined and their Fourier magnitude are plots shown in Fig. 3. All the three filters perform more or less similarly. Similar results are also obtained for high pass filter performed for the above mentioned filters. The jitters in the time domain scheme and smooth curve in the frequency domain scheme does not mean that the results of frequency domain scheme will be more accurate. This is due to the fact that in the frequency domain scheme, Fourier magnitude has been found at the same bin frequency on which convolution was performed and also the input signal comprises of exact 2^K (where K is an integer) number of samples.

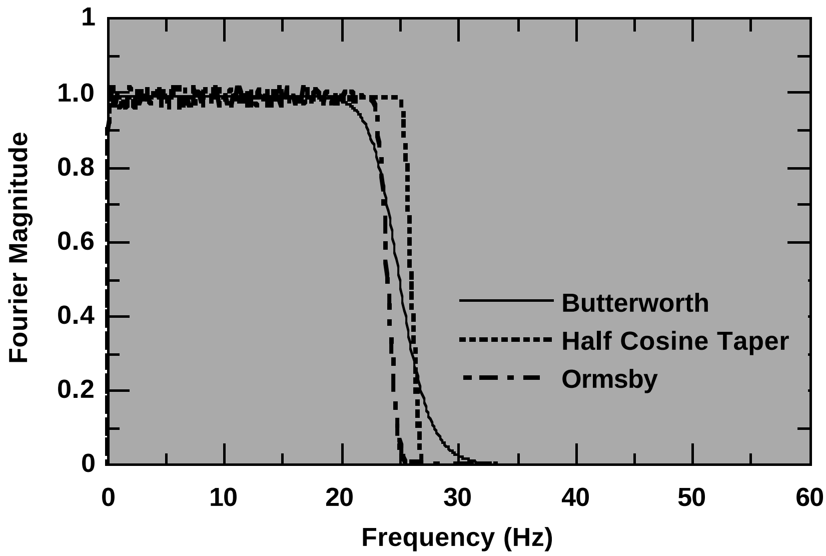

Fig. 3 Frequency Response of Different Low Pass Filters

INTERPOLATION

In Caltech scheme, the low pass filtering and instrument correction is done at 200 SPS sequence but for high pass filtering, data is decimated to 5 SPS to reduce computation and after the high pass operation the data is again linearly interpolated to get 50 SPS sequence. Also, the data at sampling rate of 50 SPS as made available to users may not be sufficient for some applications which also requires interpolation. The prevalent practice in the field of earthquake engineering is to perform linear interpolation to get the desired sampling rate. Authors in their proposed scheme and else where [5,7] have suggested use of band limited interpolation which preserves the frequency content of the original sequence. Here, synchronous noise of 2048 samples assumed at 50 SPS is taken as input. This is linearly interpolated to obtain the sequence at 200 SPS. The same signal is band limited operated to get the sequence at 200 SPS. Fourier magnitude of the above two sequences is determined and is plotted in Fig. 4. This figure shows that frequency response characteristic of linear interpolation is extremely poor. In this process substantial amount of energy in the required frequency band is lost and high frequency noise is generated. On the other hand, band limited interpolation preserves the frequency content of the original sequence. This clearly proves that in case interpolation is required, band limited interpolation should be used.

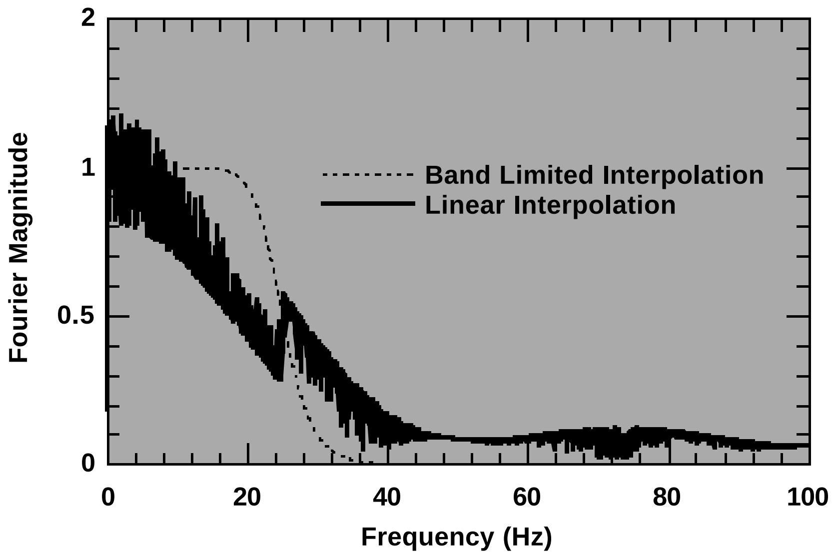

Fig. 4 Frequency Response of Band Limited and Linear Interpolation

FREQUENCY RESPONSE OF SCHEMES

A synchronous noise of 2048 sample points assumed at 200 SPS is given as uncorrected accelerogram to all the four schemes which are under study and with the same accelerometer specifications as used earlier. The cut-off frequency of high pass filter is taken as 0.1 Hz with a roll off of 0.02 Hz (if required) and cut off frequency of low pass filter is taken as 25 Hz with a roll off of 2 Hz (if required). The corrected sequence is obtained for all the four schemes. The Caltech scheme determines the corrected sequence at 50 SPS whereas Erdik and Kubin scheme, Khemici and Chiang scheme and the scheme proposed by the authors provide the corrected sequence at 100 SPS. It is assumed that the user requires the data at 200 SPS. The corrected sequence obtained from the scheme proposed by the authors is band limited interpolated to double the sampling rate. The corrected sequence obtained from Caltech scheme is linearly interpolated to increase the sampling rate by four times. The corrected sequence obtained from Erdik and Kubin scheme as well as Khemici and Chiang scheme are linearly interpolated to double the sampling rate. Fourier spectra of 200 SPS sequence thus obtained for four schemes as described above are determined and are plotted in Fig. 5. The plot indicates the effect of linearly interpolating the data. The three schemes, which are linearly interpolated, have lost substantial amount of energy from the original frequency band and instead have high frequency replicates. The worst effected is Caltech scheme where the sampling rate is increased four times as it has now three additional replicates in high frequency at the cost of lowering the contribution of the original frequency content. The Khemici and Chiang scheme and Erdik and Kubin scheme in which the sampling rate is doubled, show one additional replicate at higher frequency at the cost of lowering the contribution of frequency content of the original data. The scheme proposed by authors show a perfect overall performance and preserves frequency content of data.

CONCLUSIONS

1. This work describes the method to generate synchronous noise, which can be effectively used to get the frequency response characteristics of the process of strong motion data correction schemes. The practice of comparing performance of schemes by maximum value of history and time of its occurrence is not sufficient as it provides no information about the manner in which the scheme changes the frequency contents of the signal. This is important since in any use of strong motion data, it is the frequency contents of the data, which plays the greater role than just the values of the peak acceleration and its instant.

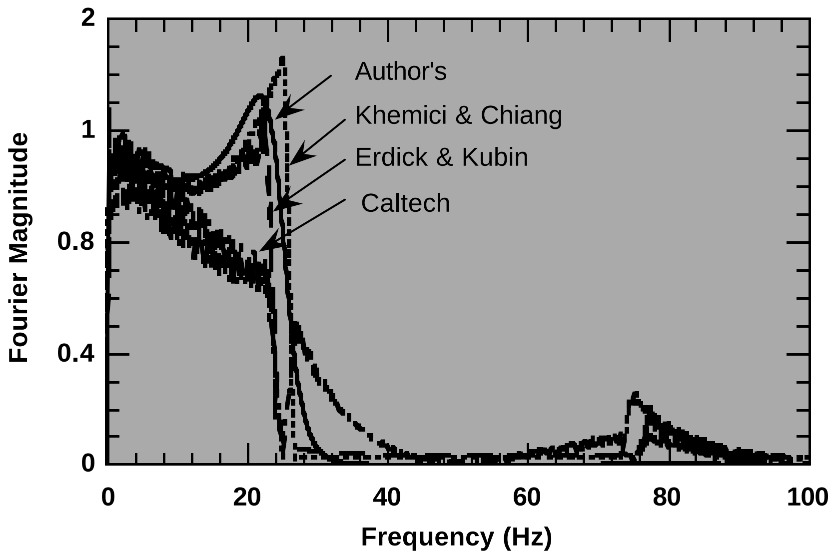

Fig.5 Frequency Response of Different Schemes

2. This work shows that the instrument correction performed in frequency domain give accurate results while using second order central difference in time domain give poor performance for frequencies higher than about 1/10 of the sampling frequency.

3. The frequency response characteristics of Ormsby filter, half cosine tapered filter and Butterworth filter determined through use of synchronous noise are found to be almost same.

4. In case the accelerogram is required to be interpolated then band limited interpolation should be used. Linear interpolation distorts the frequency content of data and this distortion is more if the factor of interpolation (ratio of sampling rate of interpolated sequence and original sequence) is higher.

5. These studies show that processing of strong motion data in frequency domain has clear advantages over working in time domain. In processing performed in time domain, the instrument correction is erratic and also a clear picture of handling of frequency contents of the data does not emerge. While working in frequency domain provides clear picture of transformation of frequency contents during processing.

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