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RECENT DEVELOPMENTS IN SYNTHESIS OF EARTHQUAKE MOTIONS USING LINEAR JOINT TIME FREQUENCY ANALYSIS TECHNIQUES

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Abstract

Temporal distribution of the frequency contents of a multi-component signal like seismic motions are not captured and well-represented in Fourier Transform (FT) techniques. Linear Joint Time-Frequency Analysis (LJTFA) addresses this issue and can transform and represent a signal in not only time domain and frequency domain, but in time-frequency domain simultaneously. Considering the better resolution and less spectral spillage when compared to Short Time Fourier Transform (STFT) and less complexity when compared to Wavelet Transform (WT), Gabor Transform (GT) is adopted in the current study. Actual recorded time-histories from recording stations in Japan had been considered for a LJTFA based synthesis of earthquake motions in this study considering the high seismicity of the area and large number of data available. Recorded time-histories of 23 earthquakes throughout Japan has been collected from K-Net and Kik-Net Strong Motion Seismograph Network of Japan and is categorized according to various Magnitude and hypocentral distances. Events of magnitude ranging from 5 to 5.5 and hypocentral distances 0 to 100km is sorted and GT is applied to transform the signals to their time-frequency domain and estimate their Gabor amplitude coefficients. Mean Gabor amplitude coefficients are estimated for different Magnitude (M_x) and Distance (D_y) combinations like M_5D_{0-25}, M_5D_{25-50}, $M_{5-5.5}D_{0-25}$, and $M_{5-5.5}D_{25-50}$. Using an inverse GT process; Gabor Expansion (GE), the mean transformed Gabor amplitude coefficients are used to reconstruct and synthesize a time-history which doesn't compromise on the quality of their spectral and frequency contents, thus yielding reliable synthetic seismic motions. Response spectra is developed from the actual and synthesized time-histories and are compared. A statistically good fit in terms of the coefficient of determination factor, R^2 is observed between the actual and synthetic response spectrum developed.

Keywords: Joint Time-Frequency Analysis; Gabor Transform; Linear TFA; Time-History; Response Spectra.

1. Introduction

Unavailability of actual recorded ground motion data have instigated engineers and seismologists to modify the spectral content to suite its applications or model and synthesize ground motions in the past. Modifying the spectral content may cause the signals to lose its reliability in dynamic studies or can create possibly unrealistic representations of ground motions. Synthesizing earthquake motions can up to an extent realistically simulate the wave propagation and tectonic characteristics of the region and can be used in dynamic analyses, structural response studies and study the rupture mechanisms during an earthquake event. The non-stationarity character of earthquake motions causes them to have time dependant variables like frequency and amplitude. For developing reliable synthetic ground motions that can be used in dynamic analyses, an in-depth understanding of this non-stationary character of seismic signals are indispensable. This had been generally neglected in the past and seismic signals had been considered stationary in widely used Fourier analyses and Transforms (FT), which break down a signal in to its principal frequency components and represent them in time series alone. To understand the non-stationary behaviour in terms of the temporal variations of amplitude and frequency contents, a Linear Joint Time-Frequency Analysis (LJTFA) technique is advocated. LJTFA techniques which are widely used in signal processing have recently generated interest in analyses of similar non-stationary signals like seismic motions. Widely used LJTFA techniques are Short Time Fourier Transform (STFT), Gabor Transform (GT) and Wavelet Transform (WT) techniques.

In and around Japan, one-tenth of earthquakes in the world occur. On an average, there is one M7 earthquake each year in Japan, and have been suffering frequent earthquake disasters even since ancient times. Japan is located along the Pacific Ring of Fire, the world's most active earthquake zone. The 2011 Tohoku earthquake and tsunami was the largest earthquake ever to hit Japan (magnitude 9.0) and this earthquake triggered a tsunami that reached a height of 40.5 meters (133 ft) and moved up to 10 km (6 mi) inland [1, 2].

Apart from its seismicity, Japan also has one of the best seismogram networks in the world. Large amount of data are collected everyday with the help of this wide network and are made available for the public through their domains K-Net and Kik-Net. These large datasets are widely adopted by researchers and engineers for seismological and geophysical studies. Most of the other highly seismically active regions in the world cannot boast of such wide seismogram networks and the ground motion data available for seismic response, region specific studies and seismic modelling are highly limited [3, 4] and warrants the generation of synthetic ground motions. Synthetic seismograms are useful for examining patterns based on various types of structures and for predicting other drawbacks in the study of structural complexity and also in applications related to geophysics [5]. In most cases, useful ground motion cannot be identified at a given location. Even if these records are available, there is no reason to expect a future earthquake to cause the same or equivalent ground movement. Thus, synthetic time-histories for specific locations need to be created for seismic time-history assessment of a structure [6]. Throughout earthquake seismology, synthetic time history is either used to match with measured seismogram data to the expected impacts of a specific earthquake, to assess the breakdown during major earthquakes or to help determine the frequency distribution [7].

Earthquake waves are always non-stationary. Seismic studies have been performed in recent decades, treating the waves as stationary. These studies lack a detailed examination of the behavior and characteristics of these movements, which includes a non-stationary study of the same. It is necessary to examine the time-frequency domain rather than the separate time domain and frequency domain, as was followed in the past decades. Because of its inadequacy in providing details of individual frequency contents, conventional techniques such as the Fourier Transforms are inadmissible for seismic record analysis. Earthquake movements have different temporal characteristics, such as amplitude and frequency, due to the earthquake wave's non-stationary behavior [8]. The critical aspect is the analysis of frequency information over the variation with time. In past years, Fourier analysis was used to describe the frequency plane in seismic signals. The Fourier spectrum integrates the frequency content in time series; however, in the spectrum above, the time location of the peak frequency and the time-frequency shift are not specified, which essentially means that it has a different time and frequency domain [9]. Time-variable spectral analyses are implemented for studying the time-frequency domain [10]. Recently adopted Linear Joint Time-Frequency Analysis (LJTFA) of seismic signals describes the change in the ground motion spectral content as a seismogram time history by mapping subsequently one-dimensional time domain signal to the two-dimensional time and frequency function and explaining how well the signal spectral data fluctuates. The joint time-frequency analysis allows simultaneous evaluation of the signal information in the time and frequency domains [11]. Time-frequency propagation often shows how much signal energy is transmitted continuously over time and in the frequency domain [12]. TFA methods consist of two methodologies: Linear TFA and Quadratic TFA. Linear TFA has been widely used in the past

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in the processing of signals and noise in various fields like communication and acoustics. Short Time Fourier Transform (STFT), Gabor Transformation (GT), and Wavelet Transformation (WT) are the most commonly used linear methods. Quadratic transformation describes the transfer of energy within signals. Wigner-Ville Distribution (WVD), Choi-William (CWD), Cone shaped distribution (CSD), and Spectrogram (SP) are various methods associated with quadratic transformation. Linear Joint TFA methods are less complex and reliable in seismic studies and has been adopted in recent studies [13]. Among the various LJTFA methods, Gabor Transformation (GT) is stronger than others because the Gaussian functions are more concentrated in the frequency domain which enables better results and resolution [6].
In a dynamic analysis point of view, one of the essential parameters of any system is its natural frequency. For a set of distinct modes, each structure has its natural frequency that affects its dynamic behavior. When a body's natural vibration mode frequency coincides with the frequency of external force, the resonance occurs leading to unnecessary deflections and possible catastrophic failures [14]. The study of the frequency quality of the signal is therefore a key step in any subsequent dynamic analyses and steps in resistant design.
An attempt has been made in this study to utilize the large number of data available from Japanese earthquakes to propose a new methodology to synthesize reliable time-histories. If found reliable, similar methodology can be adopted for regions having limited earthquake data and high seismicity, for generation of synthetic time-histories and can be used for further seismic studies and dynamic analyses. In this study, Gabor Transformation (GT) was applied on the actual recorded acceleration-time histories obtained from the Japanese domain for recorded strong motion data, Kik-NET, and Gabor Expansion (GE) is utilised to synthesize a new generalized seismogram, representing different magnitude and distance ranges for the area under scrutiny. The obtained earthquake data are sorted according to a magnitude range of 5.0-5.5 and magnitude 5 events, and hypocentral distances from 0-25km and 25-50 km. A standardized response spectrum is also developed for these magnitude and distance ranges from the synthesized time-histories.

2. Study on STFT and Gabor Transform

2.1 Short Time Fourier Transform (STFT)

The Fourier Transform (FT) does not specify exactly where the elements of time and frequency are located. Such localisation of features with time can be obtained through STFT. Short Time Fourier Transform (STFT) is the simplest illustrative time-frequency technique [10, 15]. The width of the selected window must be equal to the signal segment where the analyzed signal is believed to be stationary, and the signal's STFT is computed using FFT algorithms. The Short-Time Fourier Transforms the amplitude by linear integration as shown in Equation 1 as follows,

$$STFT\ (\tau, F) = \int_{-\infty}^{+\infty} s(t)\gamma(\tau - t)e^{-2j\pi ft}dt \tag{1}$$

Where, $s(t)$ is the time-domain seismogram, $\gamma\ (\tau - t)$ is the windowing function and $e^{-2j\pi ft}$ is the Fourier kernel. STFT is the signal spectrum $x(t)$ chosen by the location window $h(t)$ around time t. Because of the constraint imposed by the uncertainty principle, the product of STFT suffers from windowing impacts like low resolution in either domain [16], and another problem associated with STFT is the amount of spectral leakage [10]. Figures 1 (a) and (c) display STFT spectrogram images and Figures 2 (a) and (c) shows the physiogram of the sample time-history acceleration.

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2.2 Gabor Transform (GT) and Gabor Expansion (GE)

The Gabor Transformation (GT) is a unique case of Fourier's short-term transformation, where the window function used is Gaussian. Since the Gaussian Transform signals are more oriented than the frequency domain rectangular function, the frequency resolution of the Gabor Transform is much higher than the Short-Time Fourier Transforms. Gabor Expansion (GE) is an extremely useful signal processing tool [13]. Gabor Transform maps the time domain into the time-frequency domain while Gabor Expansion can be used to reconstruct the time domain signal after some time-frequency domain adjustment has been made. Gabor Expansion is defined as shown in Equation 2 and 3 as follows;

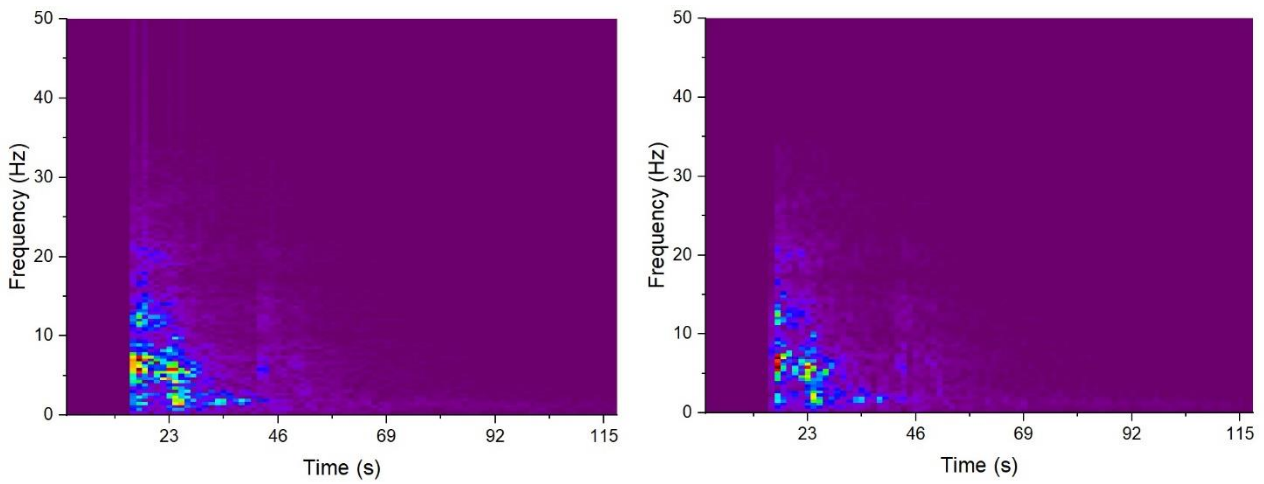
$$s(i) = \sum_{m=D}^{M-1} * \sum_{n=D}^{N-1} C_{m,n} h_{m,n}\,(i) \tag{2}$$

$$h_{m,n}(i) = h(i - mdm)\,\exp(\frac{2j\pi ni}{N}) \tag{3}$$

The coefficients $c_{m,n}$ are the Gabor coefficients, which are computed using Gabor Transform or the sampled STFT as shown in Equation 4.

$$c_{m,n} = \sum_i s[i]\gamma[i - mdm]\,\exp(-\frac{2j\pi ni}{N}) \tag{4}$$

Where the function *[i-mdm]* is called the analysis window and is a dual function of the synthesis window *h(t)*. Gabor Transformation of sample acceleration-time histories are shown in Figures 1 (b) and (d) and their respective physiograms in Figure 2 (b) and (d).



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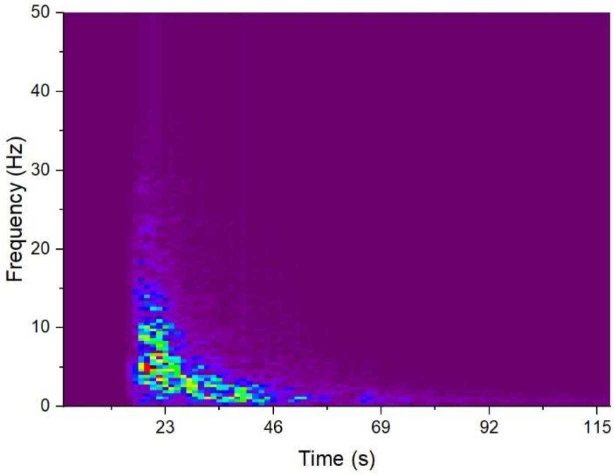

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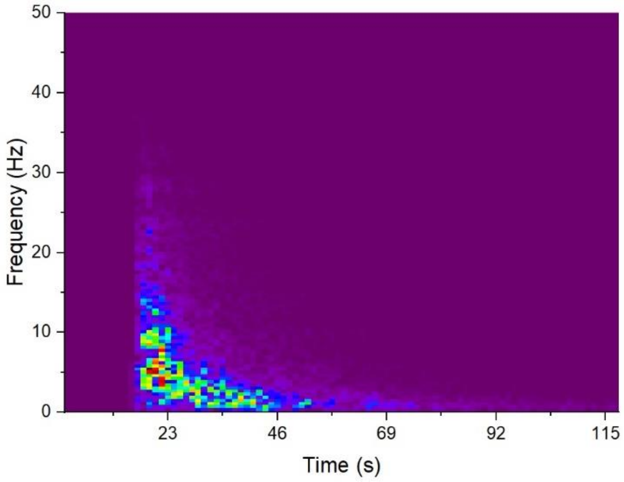
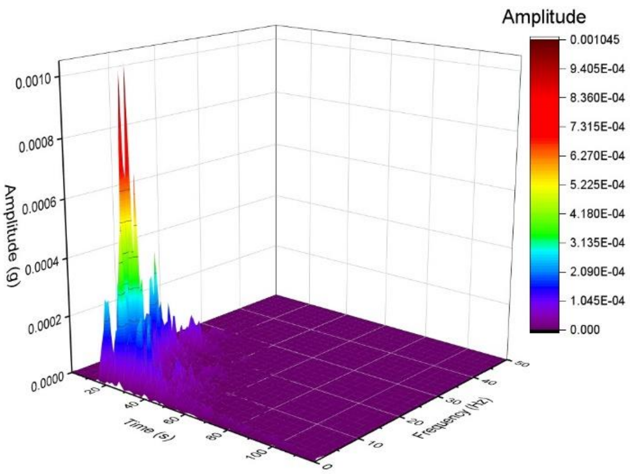


(d)

Fig. 1. Spectrogram showing the difference of STFT and Gabor Transform of sample signals of magnitude 5 and different distance ranges (a) STFT of sample signal in distance range 25-50km (b) Gabor Transform of sample signal in distance range 25-50km (c) STFT of sample signal in distance range 0-25km (d) Gabor Transform of sample signal in distance range 0-25km



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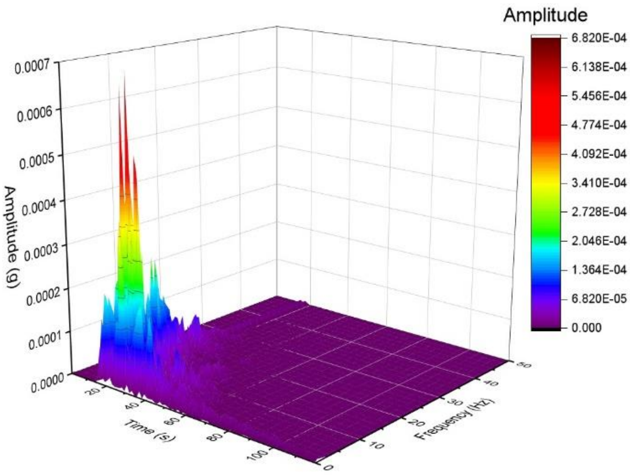

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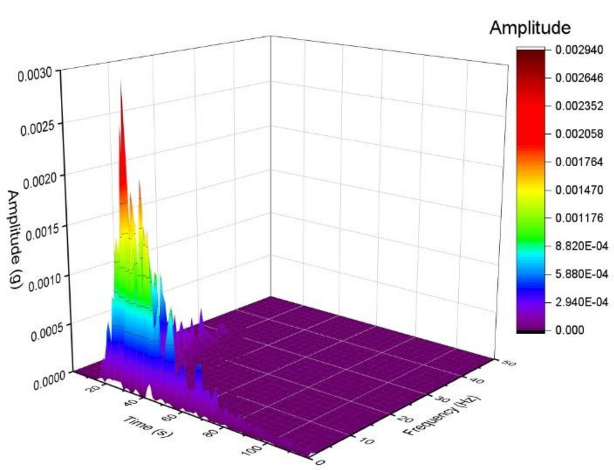

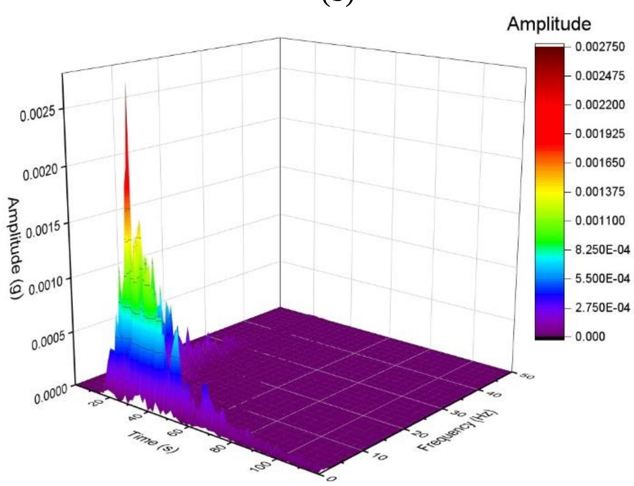

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(c) (d)

Fig. 2. Physiograms showing the difference of STFT and Gabor Transform of sample signals of magnitude 5 and different distance ranges (a) STFT of sample signal in distance range 25-50km (b) Gabor Transform of sample signal in distance range 25-50km (c) STFT of sample signal in distance range 0-25km (d) Gabor Transform of sample signal in distance range 0-25km

3. Methodology

Realistic strong ground movement is required for analyzing, evaluating and designing earthquake-resistant structures. The ground motion used for the current study was collected from the Japanese domain for recorded strong motion data, KiK-net (http://www.kyoshin.bosai.go.jp/). Earthquake waves within a hypocentral distance of 0-25km and 0-50km and magnitudes from M_j 5.0 and 5.0 – 5.5 were sorted. The whole data was thus classified in to the following Magnitude and Distance ranges: M_5D_{0-25}, M_5D_{25-50}, $M_{5-5.5}D_{0-25}$ and $M_{5-5.5}D_{25-50}$, where M_i represents the magnitude range and D_j represents the hypocentral distance range. The acceleration values of the seismogram are entirely different in range. These values cannot be merged or evaluated in a similar window and range, due to their variance. Offset correction was performed and all the corrected acceleration data is therefore divided by their individual absolute maximum acceleration to obtain a normalized time history. Consequently, the values are normalized and therefore seismograms with values varying from -1 to 1 is generated and used for further assessment.

Owing to its dominance in spectrogram quality, viz. less spectral leakage and better resolution, Gabor Transformation is adopted here among the other methods of linear joint time-frequency analysis [17]. Gabor Transformation can also accomplish inversion through Gabor Expansion, so that we can generate a new acceleration-time history taking into account the temporal frequency components [16]. All the individual normalized signals were transformed using the Equation (4) and their corresponding Gabor Amplitude Coefficients were obtained. A sample Gabor Amplitude Coefficient vs time obtained by applying GT to a normalized signal is shown in Figure 4. The mean of these Gabor amplitude coefficients of all signals in that selected magnitude and distance range is then obtained to be used in Gabor Expansion as shown in Equations (2) and (3). The reason to consider Gabor mean transformation is also to smooth out the undesirable signal characteristics like cultural noise. The response spectra of the newly developed synthetic time-history is then generated and compared with the response spectra of a random signal from the same magnitude and distance group. The flow chart given in Figure 3 below shows the TFA approach to time-history synthesis and response spectra.

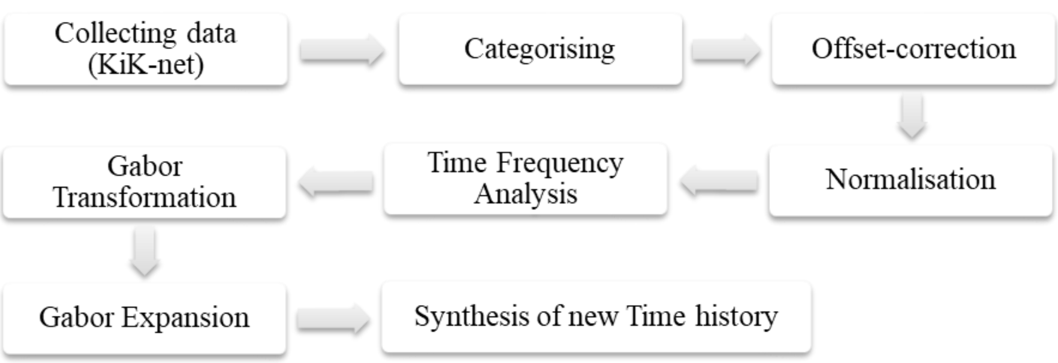

Fig. 3. TFA approach for analysis and synthesis of ground motion

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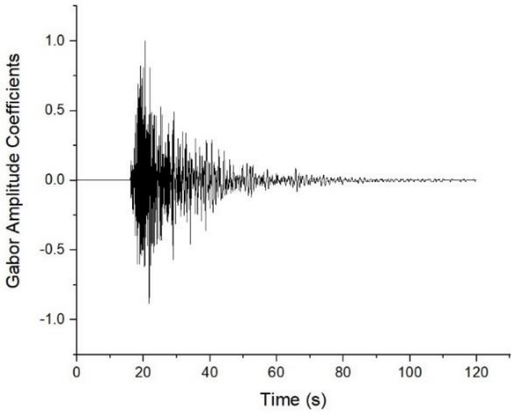
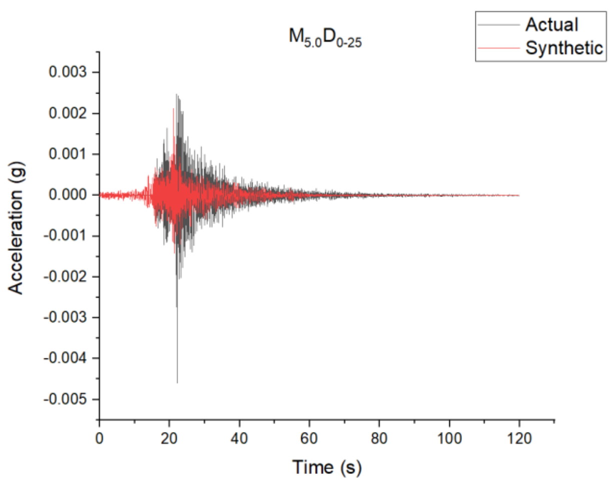


Fig. 4. Gabor Amplitude Coefficients of a sample recorded signal in $M_{5.0\text{-}5.5}D_{0\text{-}25}$ range

The response spectra thus developed can be used for further structural analysis and design and can be used to assess the dynamic activity by measuring pseudo-spectral acceleration, velocity, or displacement as a function of the specific time history and damping level [18]. A statistical quantitative check by determining the coefficient of determination factor, R^2 value between actual and synthetic response spectra is estimated to check their fit.

4. Results and Discussions

Available recorded seismograms from the selected magnitude and distance range were normalized and transformed to obtain a mean representative Gabor Amplitude Coefficient to establish a synthetic seismic signal. In order to obtain a representative synthetic seismic signal, Gabor expansion was performed on the mean Gabor Amplitude Coefficient for different magnitude and distance ranges. Good resemblance between the synthetic seismogram based on TFA and the actual seismogram can be observed from the Figure 5. Response spectra were developed for these signals and were also compared. With the actual recorded time-history and response spectra, the synthesized time-history and response spectra were found to make a good match, respectively.



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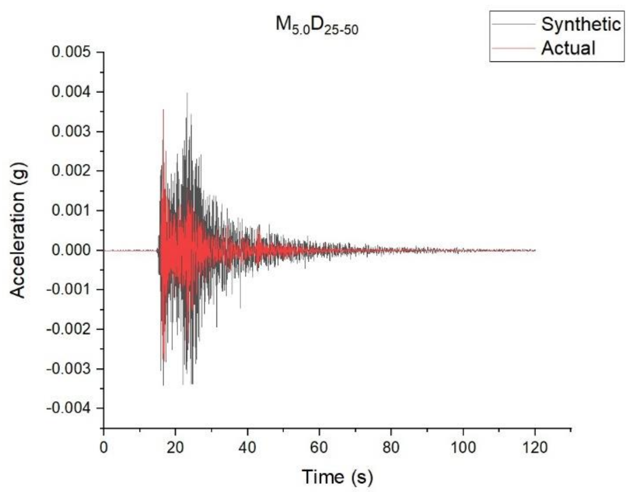

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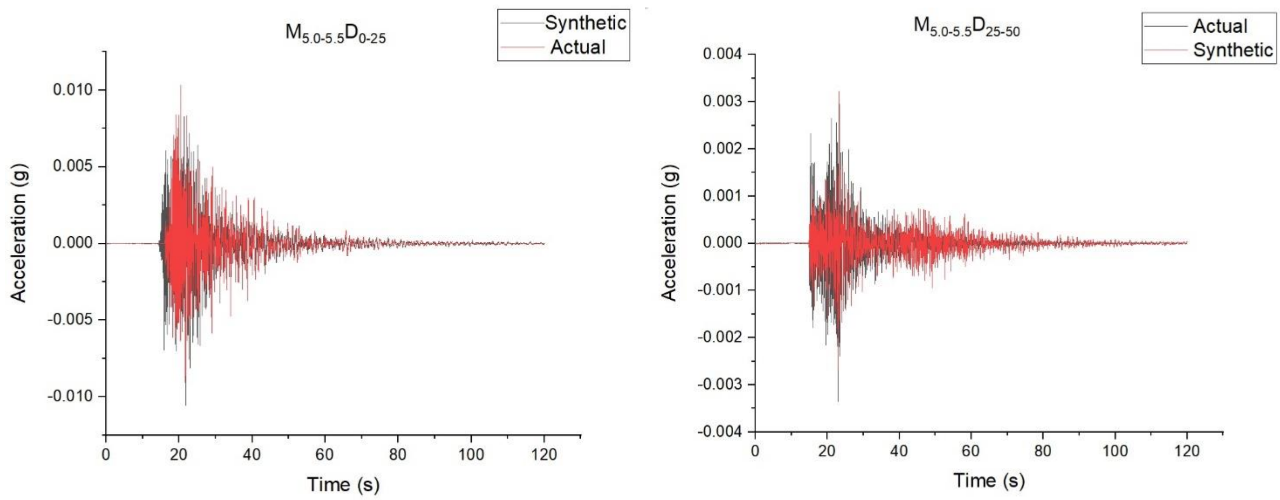
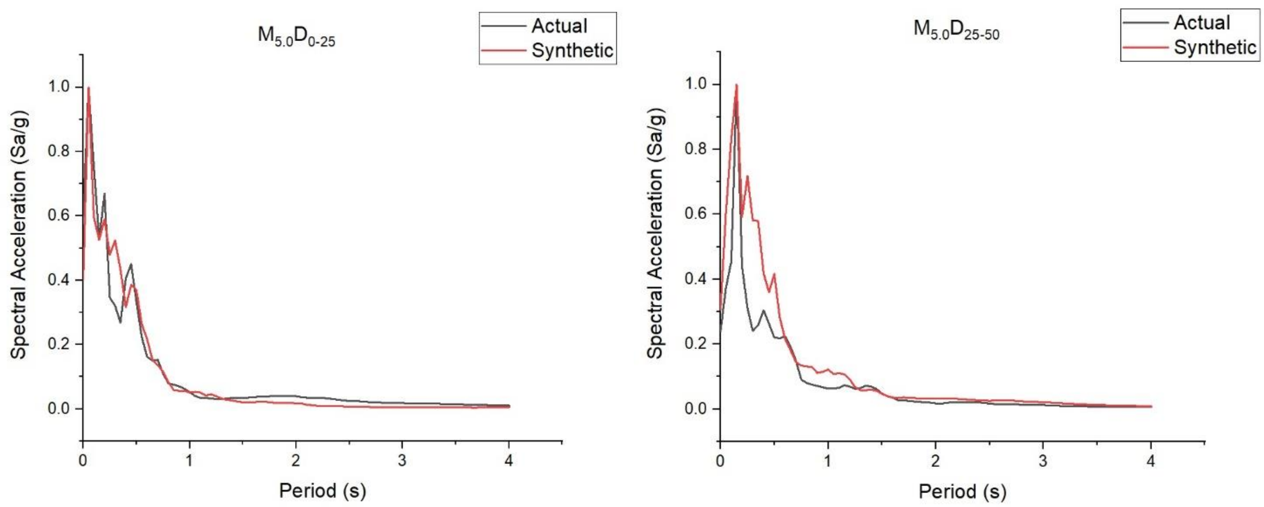


(c) (d)

Fig. 5. Comparison of the actual and synthetic seismogram (a) M_5D_{0-25} (b) M_5D_{25-50} (c) $M_{5-5.5}D_{0-25}$ (d) $M_{5-5.5}D_{25-50}$

Table 1 presents the R^2 values obtained for response spectra produced from synthetic and actual signals for all the magnitude and distance ranges. Figures 5 and 6 provide the comparison of real and synthetic seismogram and response spectra for magnitude 5.0 and 5.0-5.5 and hypocentral distances 0-25 and 25-50 respectively. The response spectra generated from synthetic time-history developed by the time-frequency approach is compared with an actual response spectrum in the same M_iD_j range. The response spectrum of actual recorded time-histories can be seen to match well with the response spectrum of the synthetic time-history. Such response spectra developed by taking into account the temporal variations of actual frequency components of the actual recorded signals can deliver reliable results when used for structural analyses.



(a) (b)

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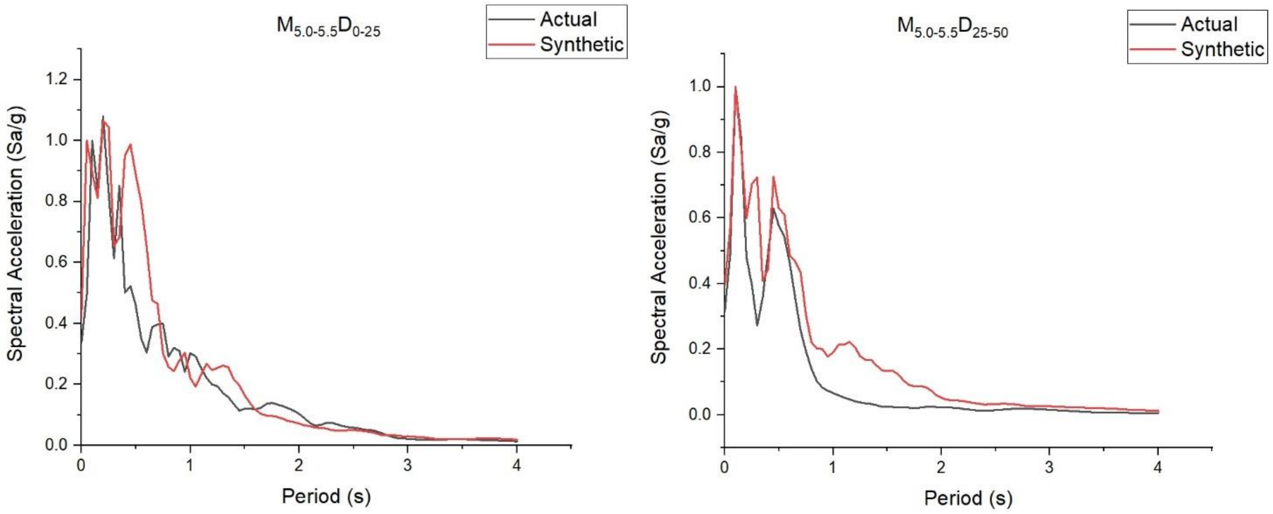


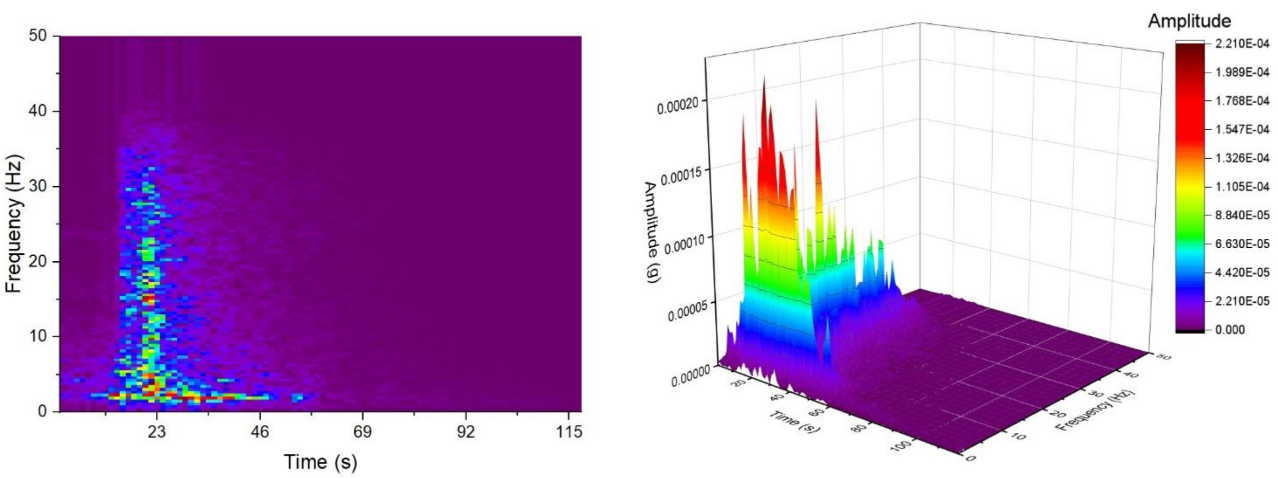
(c) (d)

Fig. 6. Comparison of response spectra of the actual and synthetic seismogram (a) M_5D_{0-25} (b) M_5D_{25-50} (c) $M_{5-5.5}D_{0-25}$ (d) $M_{5-5.5}D_{25-50}$

Table 1 - Coefficient of determination factor of seismograms for the M_iD_j ranges considered

Magnitude (M_i)	**Distance (D_j)**	**Coefficient of determination (R^2)**
M_5	D_{0-25}	0.930
	D_{25-50}	0.836
$M_{5-5.5}$	D_{0-25}	0.823
	D_{25-50}	0.848

To further evaluate the temporal frequency contents of the synthetic signals, Gabor Transform of the synthetic signals developed for each M_iD_j range are plotted along with their physiograms. Figure 7 shows the GT and physiograms of the synthetic signals developed for each M_iD_j range.



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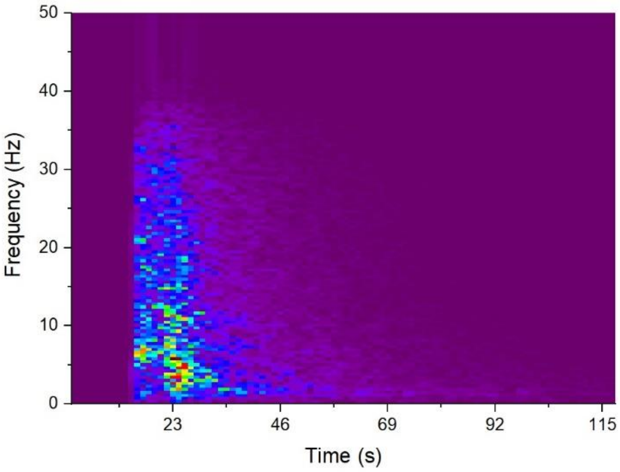

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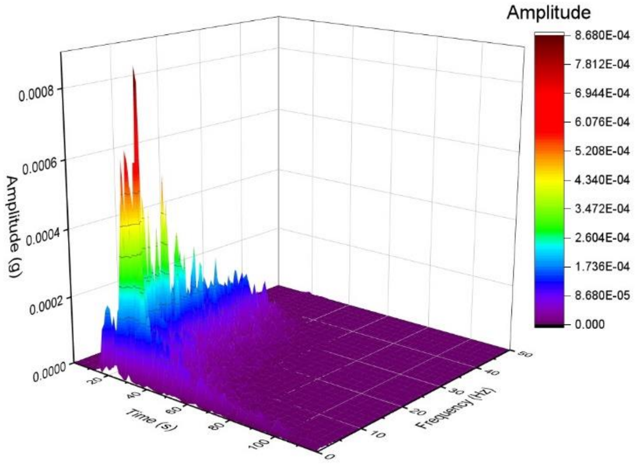

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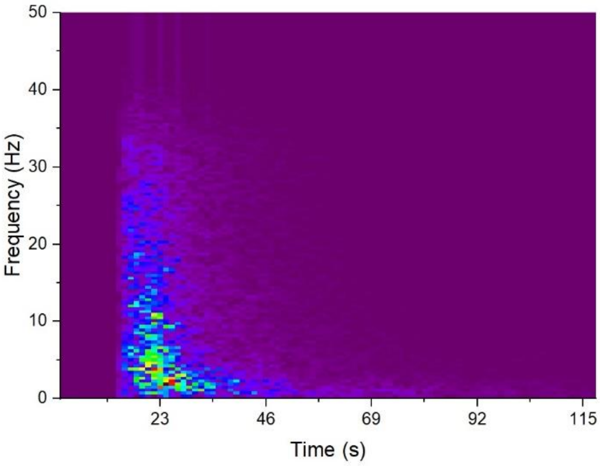

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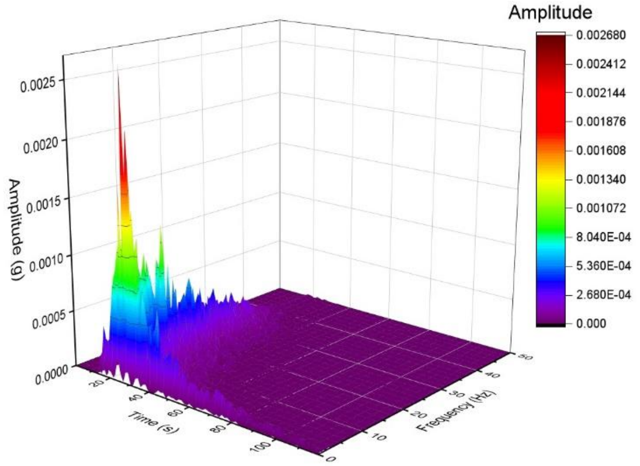

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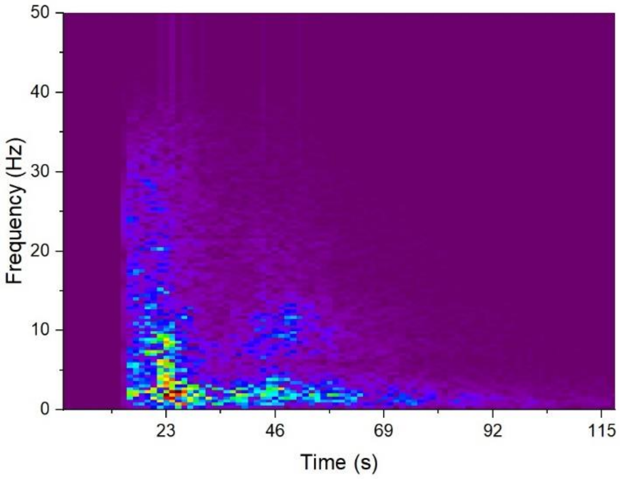

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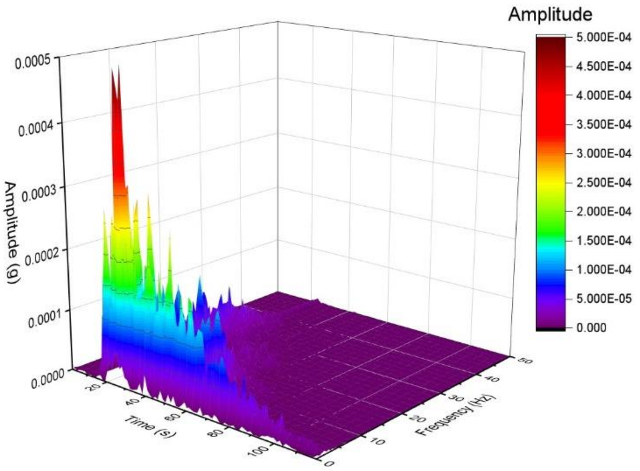

(h)

Fig. 7. GT and physiogram of synthetic seismograms of following magnitude and distance ranges (a) $M_5D_{0\text{-}25}$ (b) $M_5D_{25\text{-}50}$ (c) $M_{5\text{-}5.5}D_{0\text{-}25}$ (d) $M_{5\text{-}5.5}D_{25\text{-}50}$

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5. Conclusion

Earthquake motions synthesis is important for seismic studies in areas with minimal recorded data. The current study presents a new method and discusses some shortcomings of previous approaches to synthesize earthquake movements. The signals synthesized with Gabor Transformation and Gabor Expansion can produce better results due to their variable window functioning and less spectral leakage. The synthesized seismogram reflects closely the actual recorded seismogram but with the absence of unwanted frequencies and noise. By eliminating unwanted noise and smoothing the frequency information, a better representation of the signal characteristics and frequency contents are obtained from the synthetic response spectrum produced from synthetic seismogram. In addition, response spectra developed from synthetic time-history when compared to the response spectra of the actual time history showed that they fit the real signal pattern. The coefficient of determination factor R^2 was calculated for the original vs synthetic response spectra and was found to suit well with near unity R^2 values. The new method suggested here can be used effectively in seismically active areas with minimal monitoring stations and actual recorded seismic data for structural design, analysis and other seismic studies.

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