GROUND ROLL ATTENUATION USING IMPROVED COMPLETE ENSEMBLE EMPIRICAL MODE DECOMPOSITION

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ABSTRACT

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Empirical mode decomposition (EMD) is a fully adaptive signal decomposition algorithm. It has been used to attenuate both random noise and coherent ground roll by removing the first one or two decomposed components in each frequency slice, which acts as a dip filter to separate different wavenumber components. The mode-mixing problem is the biggest drawback of this decomposition technique, which refers to the phenomenon that the each decomposed component is related with multiple oscillating frequencies. Noise-assisted variations of EMDs, like ensemble empirical mode decomposition (EEMD) and complete ensemble empirical mode decomposition (CEEMD), can solve the mode-mixing problem to some extent but will cause other problems, such as strong residual noise and spurious artifacts. The newly developed improved complete ensemble empirical mode decomposition (ICEEMD) are intended to solve the two drawbacks of CEEMD. In this paper, we propose to apply the ICEEMD algorithm for removing the highly oscillating components in seismic data, mainly corresponding to the ground roll noise, by removing the first decomposed component of each frequency slice. The performance is compared with the FK-based and CEEMD-based approaches and is demonstrated to be very successful.

KEY WORDS: ground roll, empirical mode decomposition, mode-mixing problem,
improved complete ensemble empirical mode decomposition.

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INTRODUCTION

Empirical mode decomposition (EMD) is a new signal processing method (Huang et al., 1998), which was proposed to prepare a stable input for the Hilbert Transform. The essence of EMD is to stabilize a non-stationary signal. That is, to decompose a signal into a series of intrinsic mode functions (IMF). Each IMF has a relatively local-constant frequency. The frequency of each IMF decreases according to the separation sequence of each IMF (Chen et al., 2014). EMD is a breakthrough in the analysis of linear and stable spectra. It adaptively separates non-linear and non-stationary signals, which are features of seismic data, into different frequency ranges. Noise-assisted versions have been proposed to alleviate the so-called mode-mixing phenomenon, which may appear when real signals are analyzed. Among them, the complete ensemble EMD (CEEMD) recovered the completeness property of EMD but causes residual noise and spurious artifacts. The newly developed improved complete ensemble empirical mode decomposition (ICEEMD) are intended to solve the two drawbacks of CEEMD.

Linear noise is a type of typical noise appearing in the seismic data, such as the ground roll noise. Linear noise is spatially coherent noise, and has special properties, like apparent linear correlation, and stable velocity. They usually mask the shallow reflections at short offset, and deep reflections at larger offset (Claerbout, 1983; Saatilar and Canitez, 1988; Henley, 2003). Because of the apparent difference between the useful reflections and the coherent steeply dipping linear noise, one of the most effective ways for removing the linear noise is by applying a dip filter which rejects passing the spatially non-stationary components (linear noise) through the filter. FK-based filter is one the simplest forms of dip filters, in which the 2D fast Fourier transform (FFT) is utilized. Milton et al. (2009) proposed a SVD based dip filter to attenuate the ground roll noise, which is not an adaptive method and thus requires some parameter tuning efforts. Bekara and van der Baan (2009) initially utilized the EMD based dip filter to attenuate the ground roll. However, as described above, because of the mode-mixing between signal components and noise components, the EMD based dip filter is usually hard to implement in practice. Most of the ground-roll noise removal approaches either fail to remove all the ground-roll noise or remove much useful primary reflections energy. An efficient and effective technique for removing linear noise is always in demand.

In this paper, we propose a new ground roll attenuation approach based on ICEEMD, which maintains the adaptive merit of EMD, and cause no strong residual noise and spurious artifacts, as compared with CEEMD. Because of the better separation of the high wavenumber components and low wavenumber components, the proposed approach can obtain a much improved ground roll attenuation result, which is almost without residual ground roll.Since the EMD method has been popular due to many geophysical publications (Bekara and van der Baan, 2009; Han and van der Baan, 2013; Chen and Ma, 2014; Chen et al., 2014, 2015; Han and van der Baan, 2015), we avoid the introduction of EMD and focus only on the comparison of more advanced modifications of EMD: CEEMD and ICEEMD.

METHOD

Complete ensemble empirical mode decomposition

We assume the readers have a basic knowledge of EMD algorithms. The main idea in the noise-assisted variations of EMD is to add some controlled noise to the signal in order to create new extrema. In this way, the local mean is forced to stick to the original signal in those portions where new extrema were created while it remains unmodified in the rest of the signal (where no creation of extrema occurred) (Colominas et al., 2014). For example, the implementation of CEEMD can be summarized into the following steps:

- For I iterations, decompose $x^i = x + \epsilon_0 w^i$, $i = 1,2,\ldots,I$ by EMD

$$\mathrm{IMF}_1 = (1/I) \sum_{i=1}^{I} E_1(x + \epsilon_0 w^i) \quad . \tag{1}$$

- Calculate the first residue

$$r_1 = x - \mathrm{IMF}_1 \quad . \tag{2}$$

- Obtain the second IMF mode by

$$\mathrm{IMF}_2 = (1/I) \sum_{i=1}^{I} E_1[r_1 + \epsilon_1 E_1(w^i)] \quad . \tag{3}$$

- Obtain the other IMFs ($k = 2, 3, \ldots, K$) by

$$\mathrm{IMF}_k = (1/I) \sum_{i=1}^{I} E_1[r_{k-1} + \epsilon_{k-1} E_{k-1}(w^i)] \quad , \tag{4}$$

where r_k denotes the residue after k-th iterations: $r_k = r_{k-1} - \mathrm{IMF}_k$. When $k=0$, $r_k = x$. E_k denotes the EMD process to get the k-th component. When $k=0$, there is no decomposition. w^i denotes the i-th Gaussian white noise realization process. ϵ_k is a parameter chosen to obtain a desired SNR of residue.

Improved complete ensemble empirical mode decomposition

The CEEMD estimates the local mean of residue and subtracts it from the averaged residue. However, ICEEMD estimates the local mean and subtracts it from the original signal. In this way, we obtain a reduction in the amount of noise presented in the modes. In addition, In order to reduce this scale overlapping that causes the spurious modes, ICEEMD proposes to make no direct use of white noise but use instead $E_k[w(i)]$ to extract the k-th mode.

- For I iterations, decompose $x^i = x + e0wi$ by EMD

$$r_1 = (1/I)\sum_{i=1}^{I} M(x + \epsilon_0 w^i) \ . \tag{5}$$

- Calculate the first mode

$$IMF_1 = x - r_1 \ . \tag{6}$$

- Estimate the second residual $r_2 = (1/I)\sum_{i=1}^{I} M[r_1 + \epsilon_1 E_2(w^i)]$ and the second mode by

$$IMF_2 = r_1 - r_2 \ . \tag{7}$$

- Obtain the other residues ($k = 3, \ldots, K$) by

$$r_k = (1/I)\sum_{i=1}^{I} M[r_{k-1} + \epsilon_{k-1} E_k(w^i)] \ . \tag{8}$$

- Compute the k-th mode by

$$IMF_k = r_{k-1} - r_k \ . \tag{9}$$

Signal decomposition comparison

In order to show the decomposition performance using ICEEMD, we first use a simple synthetic example. It is 1D synthetic example, which is composed of three components, as shown in Fig. 1. Utilizing the ICEEMD approach, we obtain four components, as shown in Fig. 2, with first component as a constant zero with negligible amplitude. The other three components correspond to three well separated oscillating components with smoothly variable frequency. Using the CEEMD, as shown in Fig. 3, however, we obtain a large number of components, whose physical meanings cannot be well interpreted. We can see that there is obvious residual noise in the decomposed components and there are many spurious artifacts which cannot be explained. A time-frequency analysis by mapping the instantaneous frequency and amplitude of each decomposed signal to the time-frequency domain can be carried out to further compare the two approaches. Results are shown in Fig. 4. It is obvious that ICEEMD based approach accurately capture the frequency components, which demonstrate the better separated oscillating components.

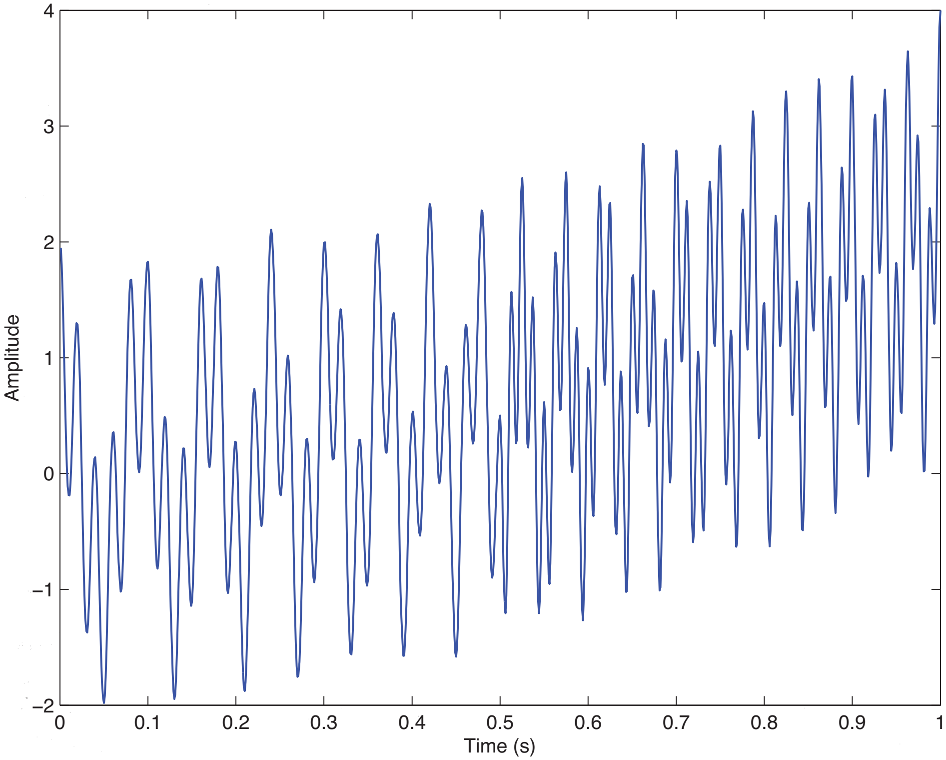


Fig. 1. Synthetic example composed of three components with smoothly variable frequency.

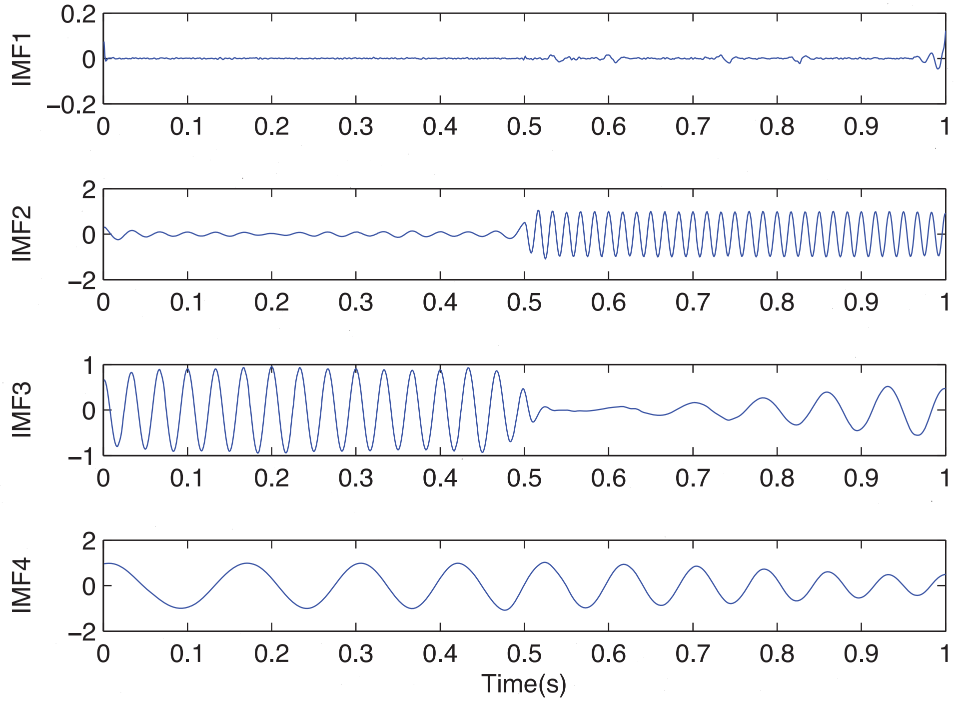


Fig. 2. Decomposed results using ICEEMD.

EXAMPLE

We propose to apply the decomposition technique to each frequency slice and remove the first component, which corresponds to the largest wavenumber component. This function is termed as the dip filtering effect of the EMD-based algorithms (Chen and Ma, 2014). We use a field seismic data as an example, which is shown in Fig. 5. There exists strong dipping coherent ground roll noise in the middle of the data. We compare the performance in attenuating the ground roll using three different approaches: the FK-based dip filter, the CEEMD-based dip filter, and the ICEEMD-based dip filter. The three results are shown in Fig. 6. Fig. 7 shows the corresponding noise sections. We can see from Fig. 6 that the proposed approach obtain the cleanest result without residual ground roll, which indicates a better separation between high wavenumber components (mainly the ground roll) and low wavenumber components (main primary reflections). There are more or less residual ground roll in the gather, which has been pointed out by the red arrows. The removed ground roll shown in Fig. 7 also shows that the ICEEMD-based approach can remove more ground roll noise (the energy of ground roll is stronger).

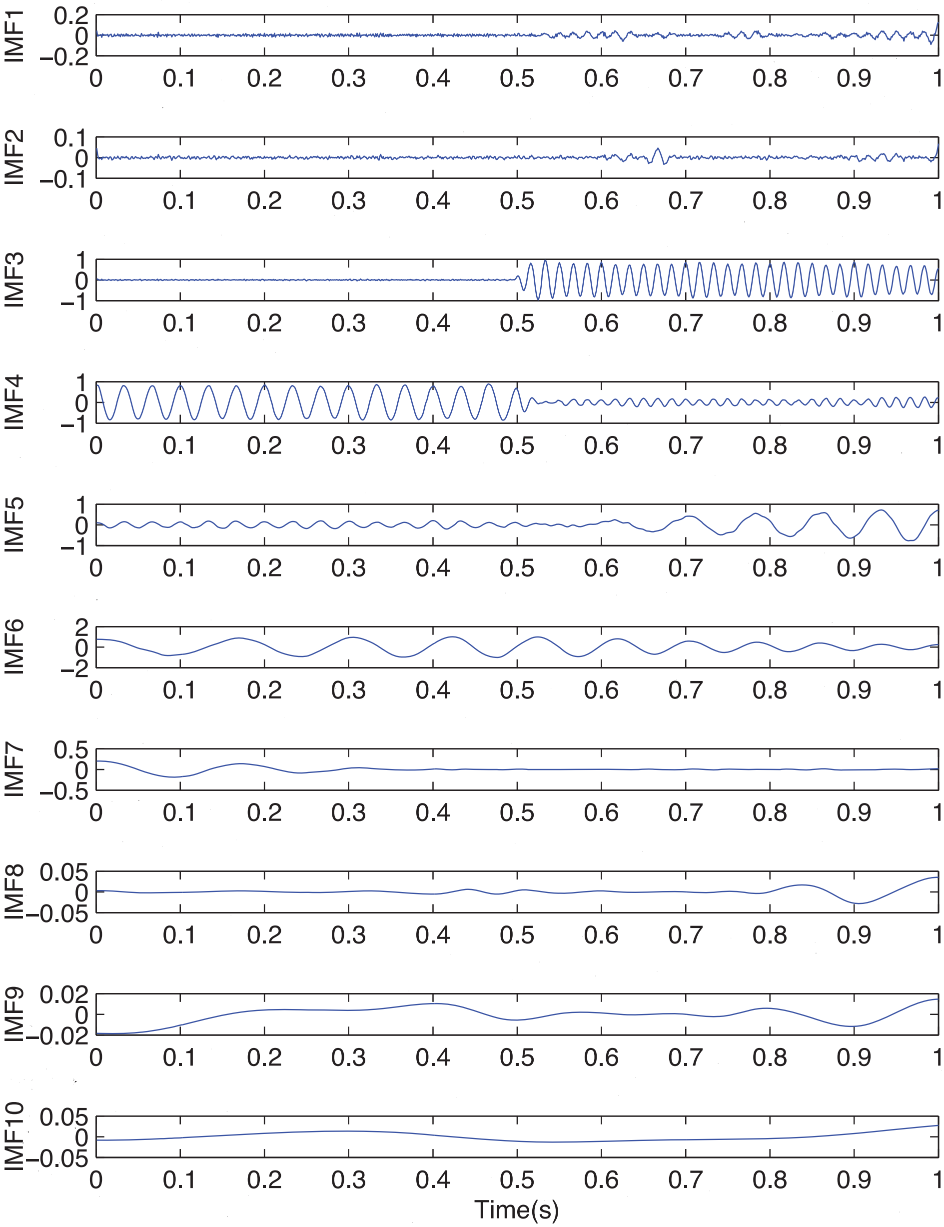
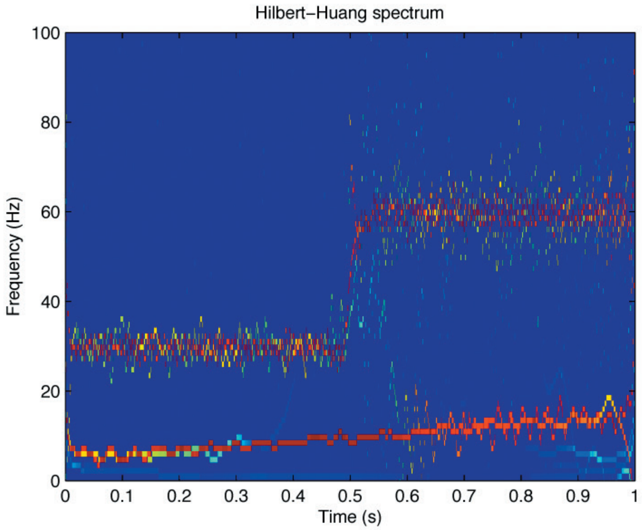
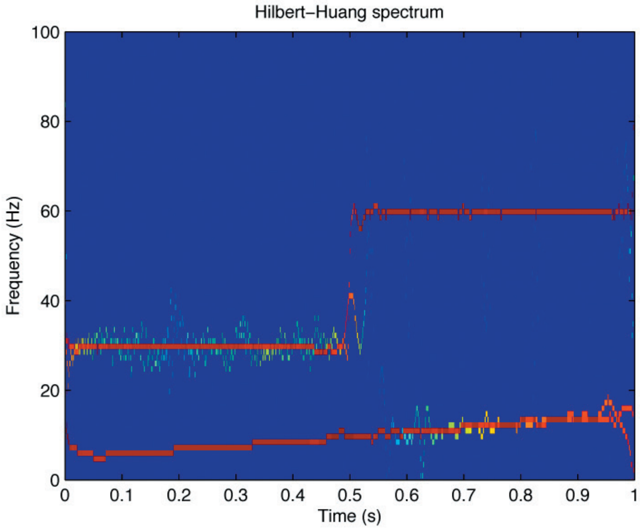


Fig. 3. Decomposed results using CEEMD.



a



b

Fig. 4. (a) Time-frequency domain using CEEMD. (b) Time-frequency domain using ICEEMD. Note that the frequency components in the synthetic example are very accurately depicted using the ICEEMD-based method.

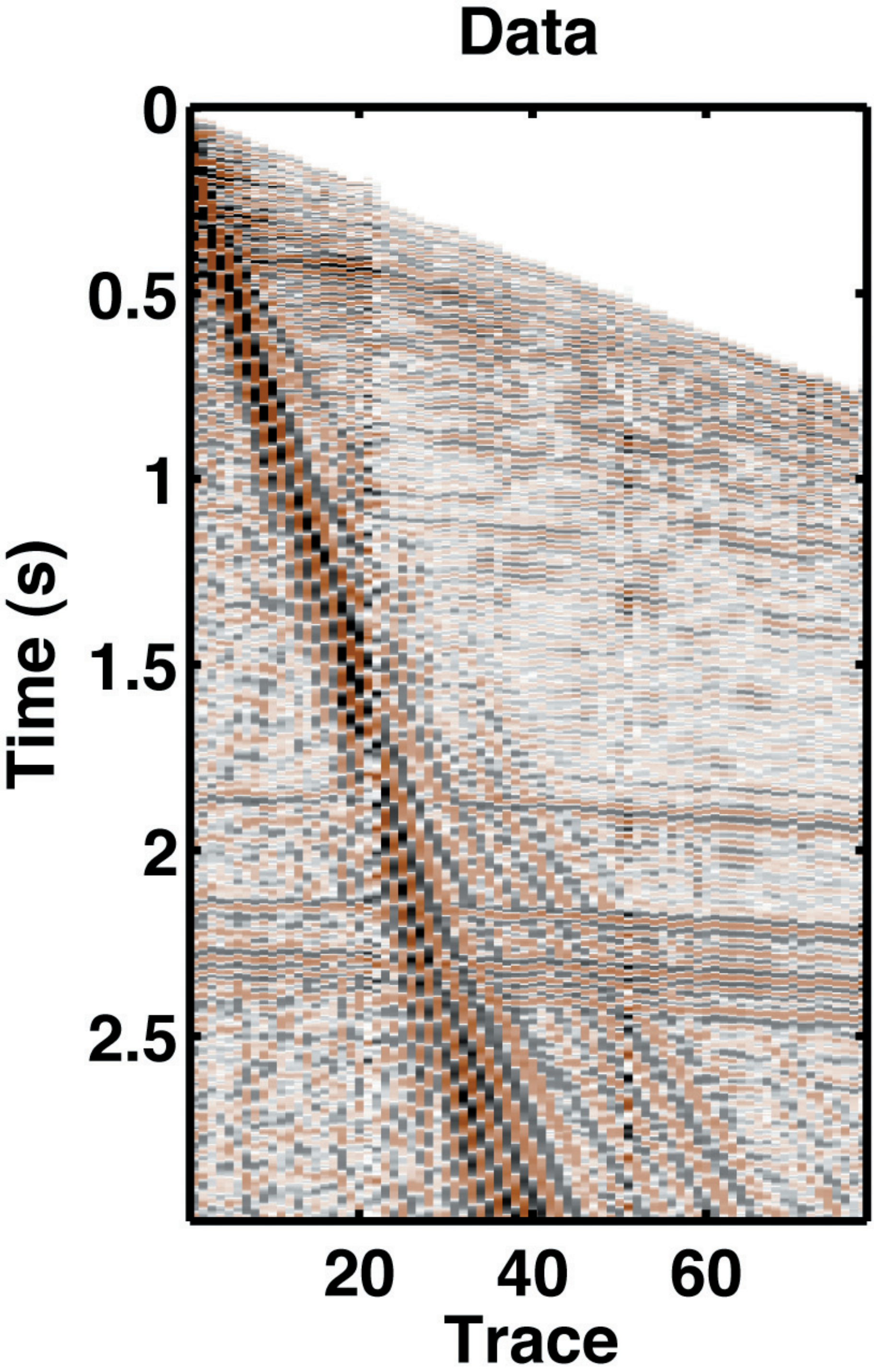


Fig. 5. Field seismic data.

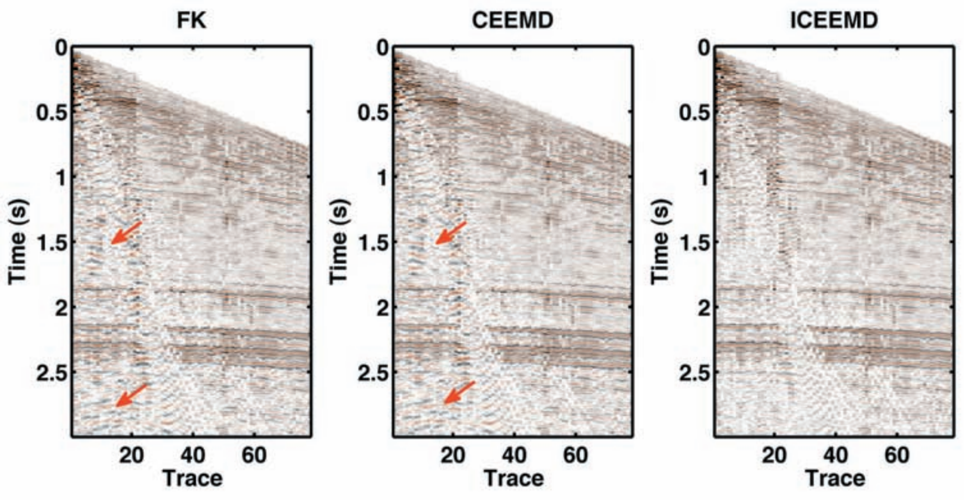


Fig. 6. Ground roll attenuated results. Left: FK-based approach. Middle: CEEMD-based approach. Right: ICEEMD-based approach.

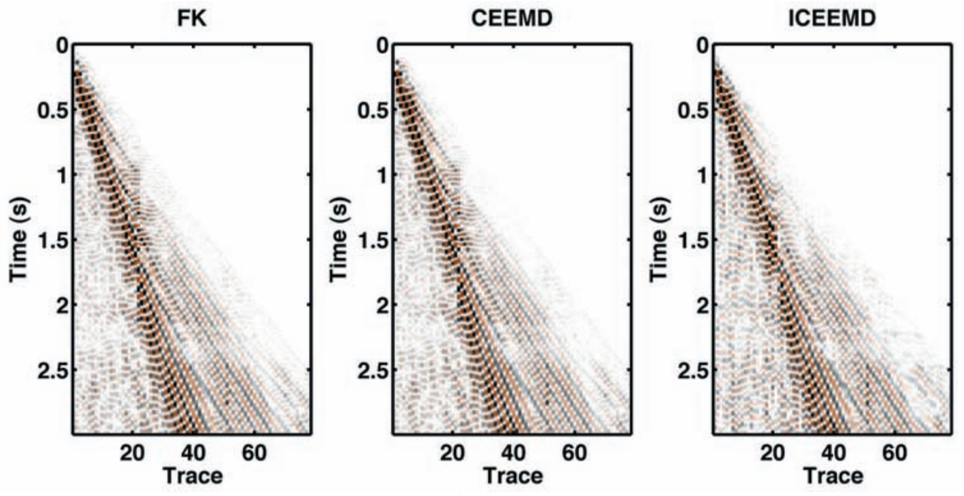


Fig. 7. Removed ground roll. Left: FK-based approach. Middle: CEEMD-based approach. Right: ICEEMD-based approach.

CONCLUSION

The CEEMD will cause residual noise and spurious components in the decomposed intrinsic mode functions. The large number of decomposed components will greatly affect the dip filtering performance since the number of IMFs to be removed is hard to decide and the spurious components will cause significant artifacts in the final result. We propose to apply ICEEMD instead of CEEMD to attenuate ground roll by removing the first decomposed component in each frequency slice. The performance is compared with both FK and CEEMD based approaches, which shows an obvious improvement and an potential to be widely used in industrial application.

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