Robust cross-correlation functions of high-speed rail system

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Abstract. The vibration propagating along the railway direction is extracted by cross-correlation method (CCM). Given two stations both beneath the railway viaduct, robust cross-correlation functions (CCF) can be obtained by stacking those of different trains. The robust CCF can be used as characteristic quantities of the wave field generated by high-speed rail (HSR). These quantities have potential to monitor the structural changes of HSR system.

1. Introduction
China is a vast country with complex terrain. According to local condition, various high and new technologies are adopted to improve passengers' comfort and ensure high speed. Malfunction in HSR system and its supporting facilities may lead to late train, economic loss, and even casualties. HSR's status of health (SOH) monitoring is urgent.

There are three major ways in HSR routine monitoring. First, deployment of various censors, whose measurements are lack of sensitivity to subtle change. Second, manual maintenance at night, which is kind of subjective. Third, comprehensive test trains, which do multi-project and high precision inspection but repeat in 10-15 days [3.7].

Here, we provide robust CCF with potential to monitor SOH of HSR system. We treat HSR trains' passing as events and retract vibrations propagating along the railway direction by CCM. Peak position of CCFs, or time differences of the signal between a station pair are stable. Robust CCF are then obtained by stacking. The robust CCF can be used as characteristic quantities, reflecting the SOH of interstation structure. The change of robust CCF may due to change in interstation structure.

2. Method
When a train is moving, there is vibration propagating along the railway direction. Choosing a station pair along the railway, time differences of this signal remain unchanged despite changes in the train's location. If the vibration is powerful enough, time difference can be derived by peak position of CCF (PPCCF) of the two stations' records. On contrary, if in different but continuous time windows, peak positions of CCF remain stable or unchanged, the main signal in that period should propagate along the railway direction.

2.1. Data
PKU ROSE Array [11] was implemented from April to May 2018 to observe road and rail generated vibrations. The data we use to validate our idea is mainly from the PK021 and PK050 stations, both of which are set under HSR viaduct. The interstation distance of the two stations is 2.4 km.
2.2. Stable PPCCF
Cutting time series of vertical component records when a train passing, we apply moving window CCM: defining 0s as the time when middle of the train above PK021 station, from -60s to 0s, for every 0.5s we take a time sample, cut an 8s-long time window, and apply CCM. The peak position of CCFs versus different time windows are shown on Fig 1(b).

![Figure 1](image.png)

**Figure 1.** Moving window CCM. (a) Waveform of two stations; (b) PPCCF versus time windows; (c) examples of CCF of six different time windows; (d) spectrums of CCF in (c). Every waveform and spectrum are self-normalized.

When the train moving closer, the amplitude of records gets bigger. It indicates train-induced vibration can be recorded even the train is several kilometers far away (Fig 1(a)). Despite low signal to noise ratio (SNR) of CCF (Fig 1(c)), the PPCCF are quite stable (Fig 1(b)), during 7-45 s before the train arriving. And the CCF are similar to each other. It can be explained by vibration propagating along the railway direction is the major signal in that time period. The stable peak position is 1.260 s, inferring the visual velocity about 1.90km/s. The low SNR is mainly due to CCF' single narrow frequency band about 5.3 Hz (Fig 1(d)). The low SNR also causes about 0.175 s to 0.195 s time shift in peak position. 45 s before the train arriving, the peak position changes, due to attenuation along far distance. 0-7 s before the train arriving, the peak position also changes, because of other more powerful near station vibration's contamination.

2.3. Vibration along the railway direction
In different situations, including different time window lengths, sampling rates, numbers of trains' carriage, train directions, and relative positions to the station pair, CCF show similar pattern: stable peak positions for a long time period, variable peak positions when the train is too close or too far. All situations show the same stable peak positions. For different station pairs, CCF show similar pattern but different peak positions [1].

The stable PPCCF illustrate the vibration propagates along the train direction. If the source is a structure induced by the train, the duration should be compatible to the duration of the train passing it,
about 5s. The much longer duration of stable PPCCF infers various source locations but same wave path difference. So the vibration must propagate along the train direction.

We prefer the wave path is the viaduct, not the ground. There are two evidences. First, the frequency spike of CCF is 5.3 Hz, which is dissimilar as the spectrum of train. Someone may argue 5.3 Hz is a combined effect of 5 Hz and Doppler effect. 5 Hz is 1.5 times of the fundamental frequency of a train at speed of 300 km/h [9], and Doppler effect make it higher when the train is approaching. However, there are slower overnight HSR trains with the same frequency spike (Fig 2). The spike can be result of vibration propagating through a structure like viaduct, but hard to figure out if the wave path is the ground. Second, the visual velocity is 1.90 km/s, which is too high for near ground soil. Concrete can reach this velocity.

![Figure 2. Spectrums of CCF of six time-windows for an overnight HSR train at speed of 240 km/h.](image)

2.4. Robust CCF
The waveform of CCF are sensitive to structure. When source meet certain conditions, Green function of a station pair can be derived from stacked CCF [4,8,10]. The change of CCF illustrate change in structure. When stacked CCF are stable while Green function is only partially reconstructed, they can still monitor structural change successfully [2].

In order to explore the potential for monitoring and improve the SNR, we stack CCF of same trains and time window to get daily robust CCF. Stacking is a common method to enhance signal and suppress noise, while the same train and time window lead to almost the same source time function and location, reducing the change of source. Then the change of CCF are attributed to the change of structure.

When the train is too far from the station pair, the target vibration is not powerful. So we choose time window when the train is closer. After stacking 32 trains' results, the CCF turn to be an about 9 s long wave packet centered at 1.260 s with small fluctuations at both sides of the wave packet (Fig 3). The wave packet's long duration is attributed to the long duration and narrow frequency spike of source.

The robust CCF of two dates show great consistency. The coherences of 16-34 s' time window but same date is between 0.916-0.945 and can be higher if we only consider the wave packet (0.963-0.983). We need to keep same source to monitor the SOH of HSR system by CCF. We determine same source locations by same time windows, but there are two challenges. First, it is hard to figure out exact time when the middle of the train is above the station. Second the same train of different date may change their velocities a little. If we choose time window between 16-34 s, the effect of location error will be restrained. The coherences of same time window but different dates are also high (0.911-0.990). With the same source, robust CCF can be used as characteristic quantities to monitor the SOH of HSR system. Monitoring the change of CCF, we can refine the change of structure [6]. High coherence in the study indicates the stable structure.

3. Discussion
We proposed robust CCF to monitor the SOH of HSR system. There are four advantages. First, repetitive similar source thanks to development of HSR transportation. Second, large amount of train events and high time resolution. Third, adaptive spatial resolution according to sensors' location and quantity. Fourth, little extra cost for monitoring.

In order to refine change in structure, there are three challenges. First, extending the duration of
stable wave packet. Short duration around 0s is hard to detect velocity change, which is more obvious and measurable in large lapse time [5]. Second, refining change due to environmental changes like rain, temperature. Third, reducing the influence of trains' change, such as velocity, weight.

![Figure 3. Robust CCF by stacking 32 trains' CCF.](image)

4. Conclusions
We apply moving window CCM to find train induced vibration propagating along the railway direction. After stacking, robust CCF are obtained. Robust CCF have potential to monitoring the SOH of HSR system.

References
[1] Bao T and Ning J 2019 Extraction of characteristics of wavefield under viaduct produced by high-speed rail Acta Scientiarum Naturalium Universitatis Pekinensis (in Chinese) 55 839-849.
[2] Hadziioannou C, Larose E, Baig A and Campillo M 2009 Improving temporal resolution in ambient noise monitoring of seismic wave speed J Geophys Res 114 B07304.
[3] Jin H 2013 Discussion on maintenance method of Beijing-Shanghai high-speed railway of Nanjing Dashengguan Changjiang river bridge Modern Transportation Technology (in Chinese) 10 51-55.
[4] Lobkis I and Weaver L 2001 On the emergence of the Green’s function in the correlations of a diffuse field The Journal of the Acoustical Society of America 110 3011–3017.
[5] Mao S, Campillo M, Hilst D, Brenguier F, Stehly L and Hillers G 2019 High temporal resolution monitoring of small variations in crustal strain by dense seismic arrays Geophysical Research Letters 46 128-137.
[6] Salvermoser J and Hadziioannou C 2015 Structural monitoring of a highway bridge using passive noise recordings from street traffic The Journal of the Acoustical Society of America 138 3864–3872.
[7] Shi Z, Pu Q and Yue Q 2017 Service performance evaluation of high speed railway long span bridge based on healthy monitoring Journal of Railway Engineering Society (in Chinese) 220 67-74.
[8] Sneider R 2004 Extracting the Green’s function from the correlation of coda waves: a derivation based on stationary phase Physical Review E 64 046610.
[9] Wang X, Chen J, Chen W, Jiang Y, Bao T and Ning J 2019 Sparse modeling of seismic signals produced by high-speed trains Chinese J. Geophy. (in Chinese) 62 2336-2343.

[10] Wapenaar K and Fokkema J 2006 Green’s function representations for seismic interferometry Geophysics 71 SI33–SI46.

[11] Wen J, Bao T, Feng Y and Ning J 2019 PKU ROSE Array: a road seismological array deployed by Peking University Acta Scientiarum Naturalium Universitatis Pekinensis (in Chinese) 55 791-797.