MONITORING BRIDGES VIBRATION USING A GROUND BASED RADAR

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ABSTRACT

Monitoring the stability of bridges under heavy traffic conditions is of paramount importance. Surveyors are interested in quantifying the amount of short-term vertical displacement due to traffic loads. A common way to measure the vertical oscillation of a bridge is by deploying reflectors/prisms on the bridge and using a total station. Alternatively lasers can be used to measure vibrations, but these are generally expensive.

In this work, we are testing the use of relatively inexpensive technology based on a Stepped Frequency Continuous Waveform radar. We have acquired radar backscattering under bridges in Milton Keynes, UK and validated the results using a video camera synchronised with the radar acquisitions.

Every time a truck was crossing the bridge an oscillation of around a millimetre was observed. Different trucks provided slightly different oscillations.

***Index Terms*—** radar, stepped frequency continuous waveform, interferometry, buildings, vibration

1. INTRODUCTION

Monitoring the amount of vibration of a bridge is very important. This information, accompanied with the temporal trend of the displacement can be used to evaluate if the bridge requires repairing. Councils need an inexpensive but accurate way to prioritise the works on bridges that may need earlier attention. This is of special interest for new twentieth-century towns (such as Milton Keynes, UK) since the most of the bridges infrastructure were built at around the same time.

A common way to measure the vertical oscillation of a bridge is by deploying GPS receivers or prisms on the bridge and using a total station [1, 2]. This solution is time consuming, since we need to access and solidly install a prism onto parts of the bridge which are of most interest (often the bottom). Alternatively one could use lasers, which will allow to measure vibration without need to directly access the bridge deploying prisms. However, lasers of this kind are very expensive and they need a very careful handling of the equipment.

In the recent years, some researchers started using radar interferometry for this purpose [3]. Radars have the benefit of not necessarily need to deploy a reflector (as long as the antennas are large enough) and they can provide quick measurements that will be able to capture the fast oscillations. Additionally, they are able to cover extended areas of the bridge, providing measurements that are not relative to a single point.

2. METHODOLOGY

2.1. Basic idea

In this work, we propose to measure bridges vibration by using ground radar interferometry and improve the detection of vibrations in the interferometric phase. The radar will be sending pulses at a frequency that can be set, but it is generally higher than 10 Hz. The pulses will interact with the target (in our case a bridge) and they will be scattered back to the radar. After the focusing, the phase of the response for a defined bin of the signal will be related to the distance of the radar to a point on the bridge. If a vibration is present, this phase will change. Therefore, by subtracting the phases of two consecutive pulses we can estimate the movement of the bridge between the two time instants where the pulses were sent/received. This is assuming that the distance is not too high and the travel time of the wave is much smaller than the intervals between two pulses. This processing is analogous to the zero baseline interferometry processing done with SAR images.

In [3] a study using radars was proposed to evaluate vibrations of bridges due to a train passing. In this work we are focusing on smaller traffic (e.g. truck) and designing algorithms to improve the detection of smaller vibrations.

2.2. Radar system

The radar system is based on a Stepped Frequency Continuous Waveform radar. This means that the radar is transmitting a wave at a fixed frequency (with a very small bandwidth) and the frequency is changed in steps between an initial and final frequency value. This will form the band that the radar system is using. This processing has some similarity with a linear frequency modulation done with pulsed radars (i.e. the chirp signal), however the signal is discrete in frequencies and the radar is transmitting the signal continuously from start to end of the frequency sweep.

The processing is simply accomplished by applying an inverse Fast Fourier Transform (iFFT) to the received signal.

Table 1. Parameters used by the SFCW radar

Parameter	value
Initial frequency	5 GHz
Final Frequency	6 GHz
Slant Range resolution	15 cm
Power	0 dBm
PRF	33 Hz

The radar system we used considered the parameters showed in Table 1.

3. RESULTS

3.1. Measurement setting

Experiments were performed under concrete bridges in Milton Keynes. Here we will present the results obtained during the experiments in August 2017 under the road A421 in Milton Keynes (UK). The bridge is just outside the Open University campus and A421 is a double carriage and is one of the arteries of Milton Keynes running east-west. On average, it has a traffic of 24424 motor vehicles a day and approximately 5% of this corresponds to truck and heavy vehicles (data from the Department of Transport, UK).

Figure 1 shows the setting of the experiment.

3.2. Results

Figure 2.a presents the backscattering image after focusing. The horizontal axis represents time, while the vertical axis is distance to the radar. The backscattering is high at a distance of 1.8 m from the radar. This is due to the first return coming back to the radar. As expected, the backscattering profile looks stationary during the full acquisition. In order to be able to use the phase of consecutive pulses it is important to check that this is coherent in time. A measure of the time coherence is obtained by performing a coherence estimation along the horizontal axis (i.e. time). This is showed in Figure 2.b using a moving window of 5 bins.

To evaluate the displacement we can estimate the phase difference between consecutive bins and use the relation with the wavelength to convert this into a displacement. The result is showed in Figure 3.a.

The displacement shows a series of peaks. The largest peaks have a common behaviour. The bridge moves closer to the radar then it springs away from the radar. The largest of the peak suggests a displacement of around 0.3 mm. Most of these peaks are due to heavy traffic on the bridge. This was validated by using a camera on the top of the bridge monitoring the traffic. This experiment was repeated several times and in each instances we could observe that if an heavy vehicle is crossing the bridge, then an oscillation is visible. However, some of the small spikes were no due to any heavy vehicle (they are due to noise or movements of the radar).

3.3. Noise

To test the amount of expected noise, we did another experiment pointing horizontally the radar beam to a concrete pylon of the bridge. This is not supposed to vibrate along the horizontal direction. The measured displacement was then collected to form an histogram that is showed in Figure 3.b. The histogram is showed as blue dots while the green line represent the best fit of a Gaussian distribution. It appears that the displacement noise is zero mean but it is not Normal distributed. Although the displacement noise is relatively small we can observe few instances showing very large values of displacement.

4. IMPROVING DETECTION

In this section we propose some processing that can improve the identification of peaks related to genuine displacements. We have seen that the noise is zero mean, therefore it will be beneficial to apply some smoothing box car filter, as long as the size of the boxcar is not larger than the width of the peaks corresponding to the vibration. The width depends on the fundamental frequency of vibration of the bridge. In this experiment, the width was larger than 3 bins, therefore we applied a boxcar filter of 3 bins. The result is showed in Figure 4.a.

The result improved, but the noise is still high. We can notice that all the genuine peaks have the same signature in time. The duration of one vibration depends on the bridge characteristics, while the amplitude of the vibration depends on the load on the bridge. Therefore we can apply a matched filter based on the empirical response of a target. Looking at the image this appears to be one period of a triangular wave of around 10 s duration. The matched filter can be accomplished using a convolution in the frequency domain.

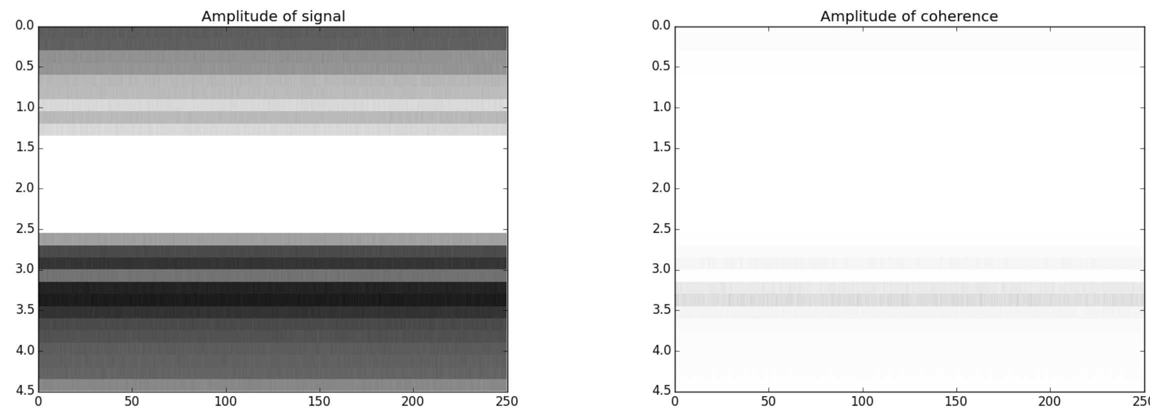
The result of this processing is presented in Figure 4.b. It can be observed that after the filtering the displacement presents a peculiar signature (two small peaks down and one up). An automatic system can trigger a detection based on the value of the central peak or the sequence of the three peaks. When the filter is applied to data collecting only noise, the final signature is not present.

5. CONCLUSION

In this work, we utilised a Stepped Frequency Continuous Waveform (SFCW) to monitor vibrations of a bridge. This was done by measuring the phase difference between two consecutive acquisitions when a repetition of 33 Hz was used.

The experiments showed that we can monitor vibrations of fractions of millimetres. We also analysed the noise as-

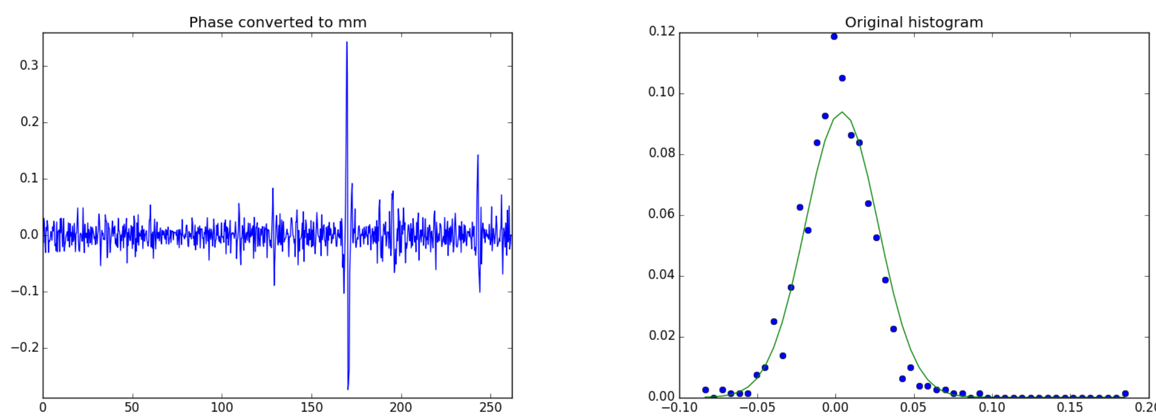
Fig. 1. Setting of the experiments under the



(a) Backscattering

(b) Temporal coherence

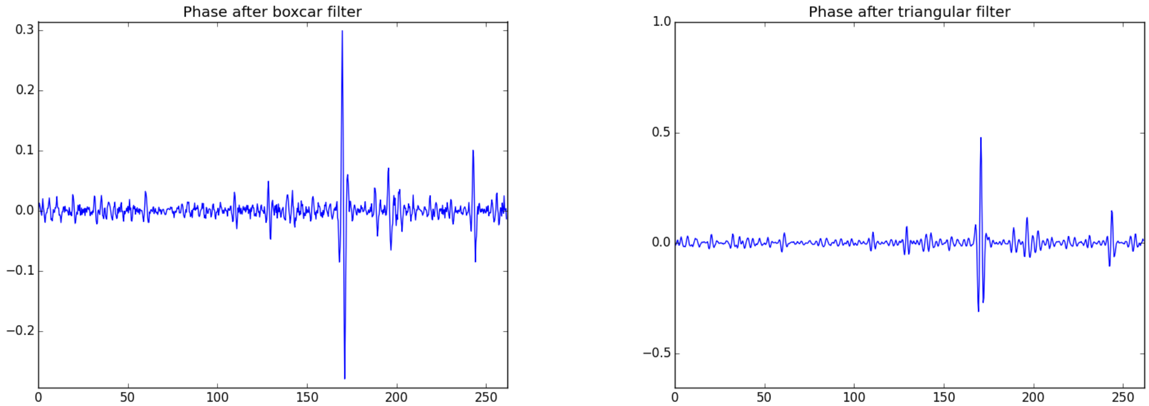
Fig. 2. Results of experiments on 4^{th} August 2017. (a) HH backscattering magnitude; (b) Temporal coherence (Box filter: 5 bins. The horizontal axis is time in seconds, the vertical axis distance in meters.



(a) Displacement

(b) Smoothed displacement

Fig. 3. Results of experiments on 4^{th} August 2017. (a) Displacement in mm; (b) Blue dots: Histogram of displacement in mm, green line: fitting with Gaussian.



(a) Displacement

(b) Smoothed displacement

Fig. 4. Results of experiments on 4^{th} August 2017. (a) Displacement after box car filter (3 bins); (b) Displacement after matched filter with triangular wave.

sociated to the measurements and devised a filtering stack to help extract genuine peaks from the noise background.

In the future more experiments will be done with different bridges and structures.

6. REFERENCES

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