Experimental validation of a non-contact, non-line of sight displacement sensor for SHM

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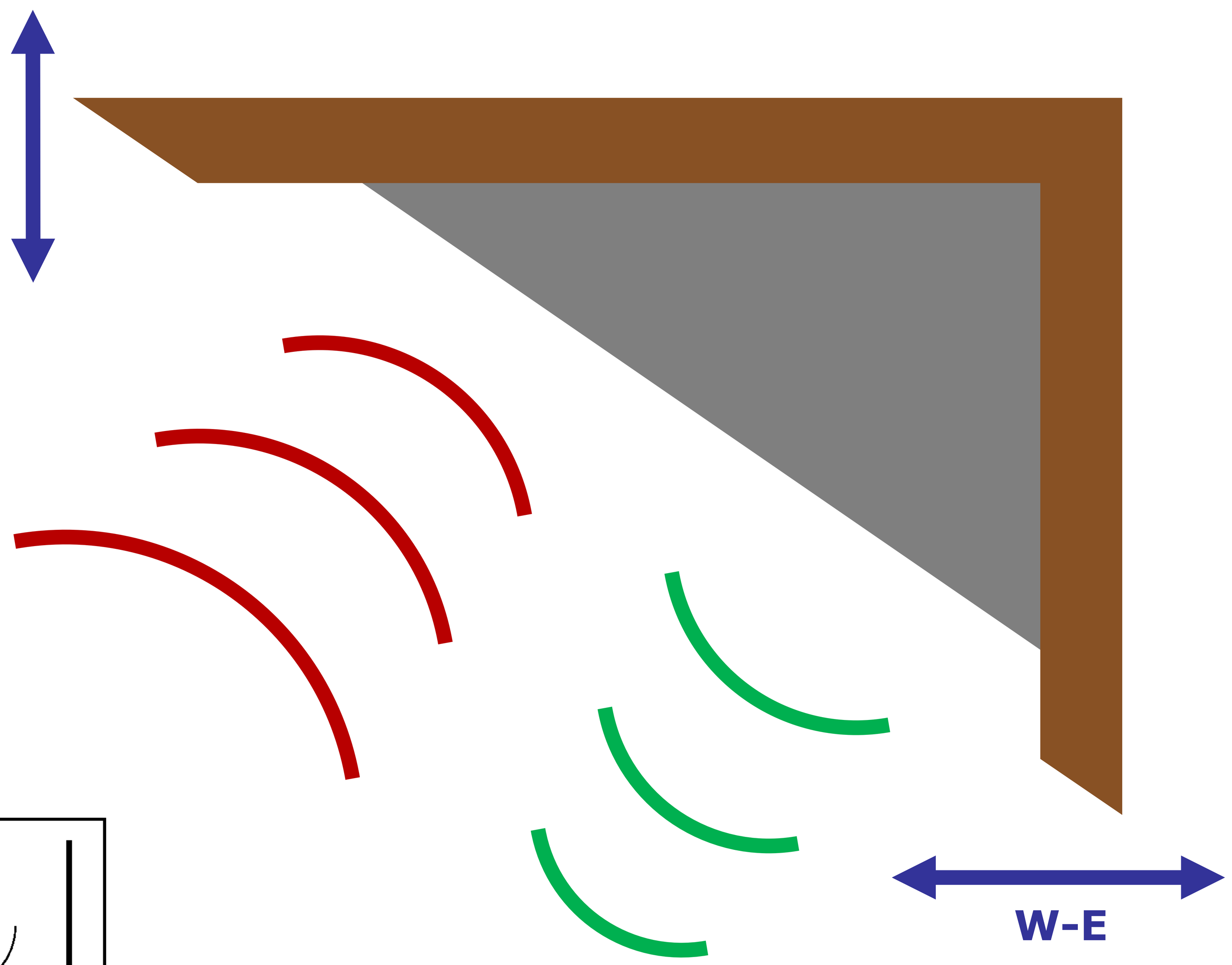
Abstract

- This work investigates the possibility of developing a non-contact, non-line of sight sensor to measure interstorey drift through simulation and experimental validation.
- The method uses frequency-modulated continuous wave (FMCW) radar to measure displacement. This method is commonly in use in a number of modern applications, including aircraft altimeters and automotive parking sensors.
- The technique avoids numerous problems found in contemporary structural health monitoring methods, namely integral drift errors and structural modification requirements.
- The smallest achievable detection error in displacement was found to be as low as 0.26%, through simulated against the displacement response of a single degree of freedom structure subject to ground motion excitation.
- This was verified during experimentation, when a corner-style reflector was placed on a shake table running ground motion data taken from the 4th September 2010 earthquake in Christchurch. These results confirmed the conclusions drawn from simulation.



Frequency-Modulated Continuous Wave Radar

This particular radar system continuously transmits a signal with a time-variant frequency and compares it to received echoes to ascertain the signal's time of flight. The channel response indicates the location of reflectors in the vicinity of the transceiver.

The frequency of the transmitted signal typically varies in a linear or quadratic fashion over time; an example of this FM signal is depicted in Figure 1. Upon reception of the echoed signal, it is multiplied by the signal currently being transmitted; in other words, the received signal is a delayed copy of the transmitted signal.

It can be shown that the frequency component of the mix (or multiplication) of transmitted signal and the received signal at the same time corresponding to a particular target can be related to the distance to the target by:

$$d = \frac{c \times T_{\text{mod}}}{2(f_1 - f_0)} \times f_r$$

Here, T_{mod} is the period over which the linear frequency sweep occurs, and f_0 and f_1 are the minimum and maximum frequencies used in the frequency sweep. The distance resolution of this system is inversely proportional to the sweep bandwidth.

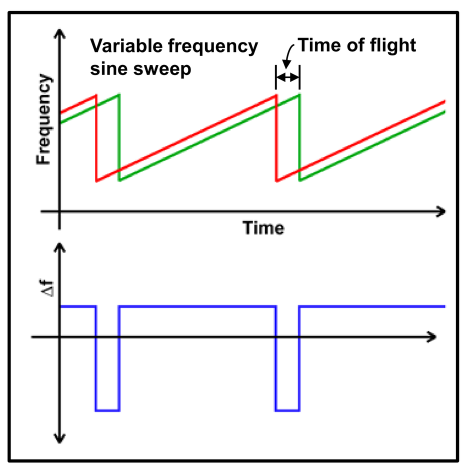


Figure 1
Red: Tx Signal
Green: Rx Signal
Blue: Difference in Tx and Rx frequency

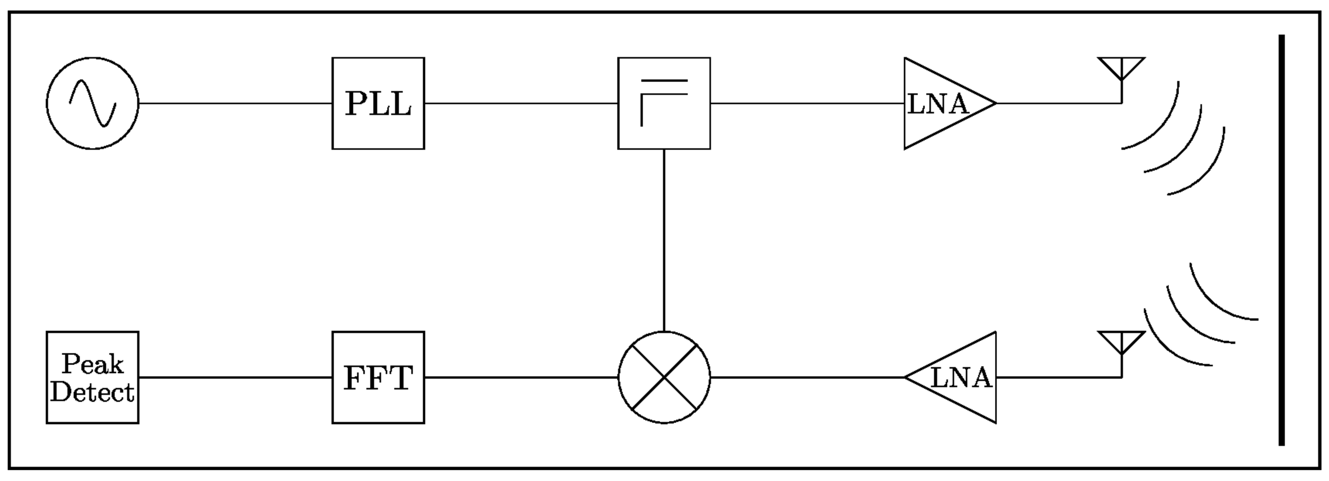


Figure 2 A block diagram of a FMCW system

Simulation

The suitability of a FMCW radar SHM system was verified using MATLAB simulation. The data used to simulate a moving target were taken from real-world displacement data obtained during the 4th September 2010 earthquake in Christchurch, New Zealand. The data set, obtained from a single degree of freedom structure in the Christchurch Botanical Gardens, was 150 s long and sampled at 200 Hz.

The simulated resting distance between the detector and target was set to 20 units, with the maximum instantaneous displacement scaled to ±1 unit, for an IDR of 5%. Additionally, some additive white Gaussian noise was inserted (20 dB signal-to-noise ratio) to determine that the system is robust to some noise. This ensured that the simulation would be an accurate representation of a system with a bandwidth range of 200 MHz to 20 GHz.

Significant improvements in accuracy are achieved as the system bandwidth increases. The best performance of the FMCW simulation was a mean error of 5.125 units, for a target 2000 units away, with a sweep bandwidth of 78 MHz. This is equivalent to a smallest achievable detection error of **0.26%**.

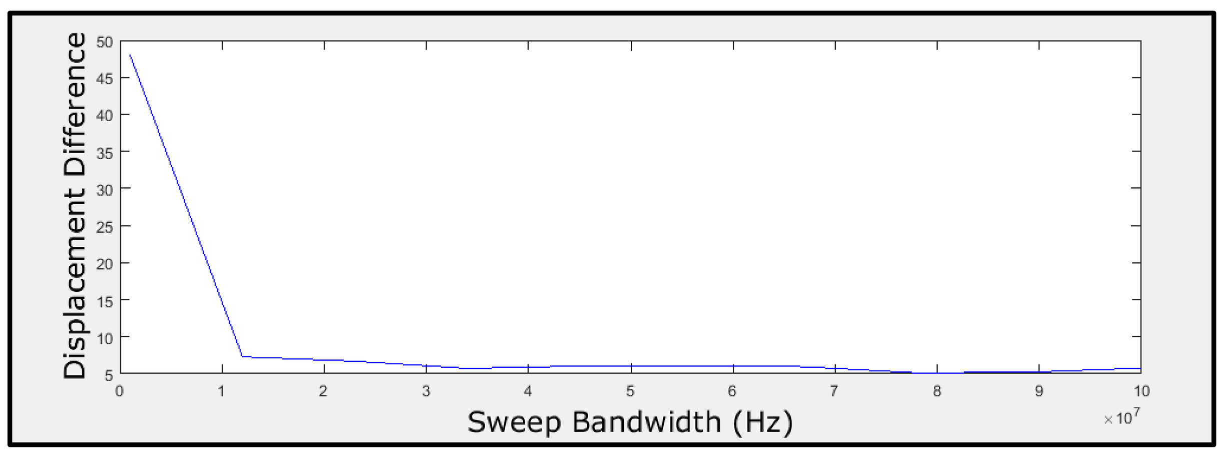


Figure 3
A demonstration of the improvement of FMCW system performance as the system sweep bandwidth is increased.

Experimentation

Experimentation was carried out to validate the simulation results obtained earlier, in terms of both displacement accuracy and ability for high frequency signals to be used in a noisy, multipath environment. A 700 MHz bandwidth test rig (centre frequency 9.75 GHz) was used to measure ground motion on a shake table at the University of Auckland.

Numerous ground motion data sets were tested, with the mean error between LVDT and FMCW sensors being **1.94%**, indicating that the method is suitable.

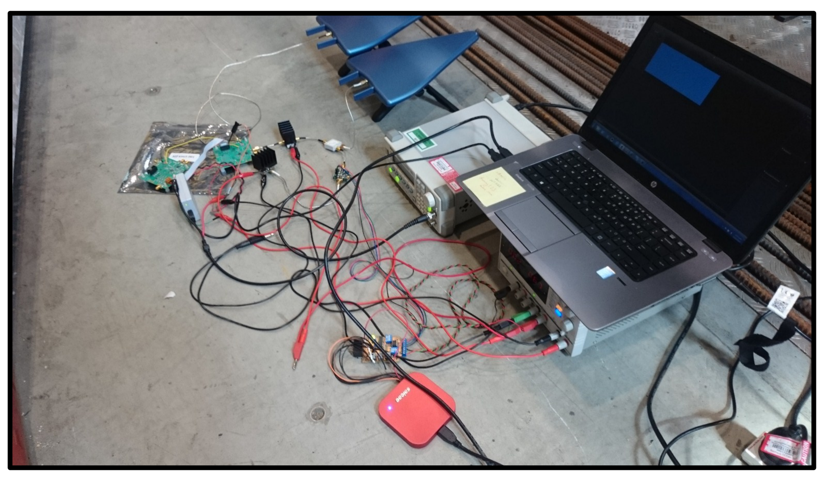


Figure 4
The FMCW prototype

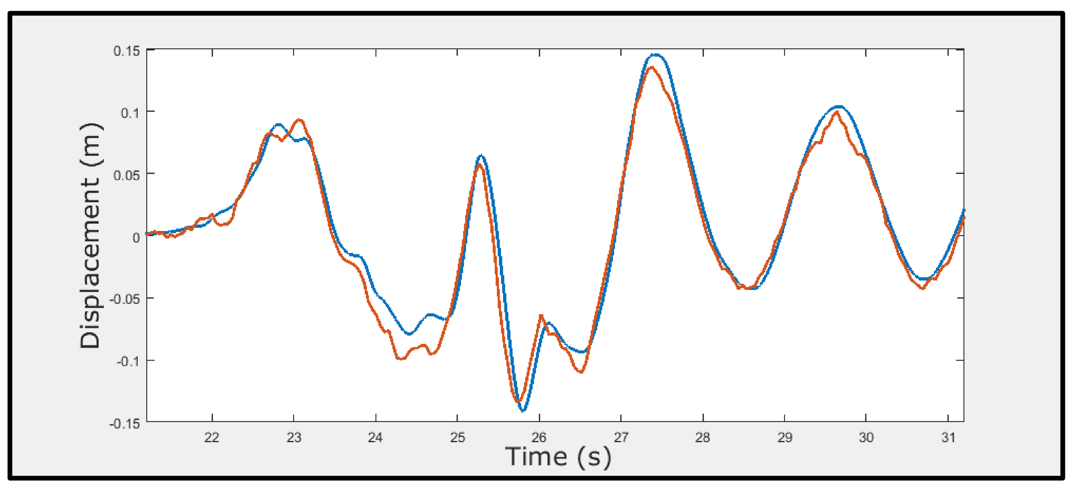


Figure 5
An example of FMCW sensor data (orange) against LVDT ground motion data (blue) of REHS data from the Canterbury earthquake, 4th September, 2010.

Reflector Design

The reflector used for experimentation was a model manufactured using sheet aluminium (1.5 mm thick) in the shape of a cube corner, and can be seen in Figure 6. This style of reflector is commonly used in radar systems due to its retroreflectivity (ie. RF signals are reflected along the same path as the incident wave with minimal scattering), maximising the signal energy at the receiving antenna. These reflectors have a viewing angle of about 35°, suitable for SHM applications.

Corner reflectors ensure that reflected signals travel the same distance when entering and leaving the open reflector face (Figure 7 demonstrates this). This ensures that the radar system will report a single distinct displacement for reflections from a particular receiver, rather than a spread of distances dependent on the angle at which the wave reached the reflector.

This reflector design is suitable for installation in a structure, as it should fit the corner of a structure without any modification necessary.

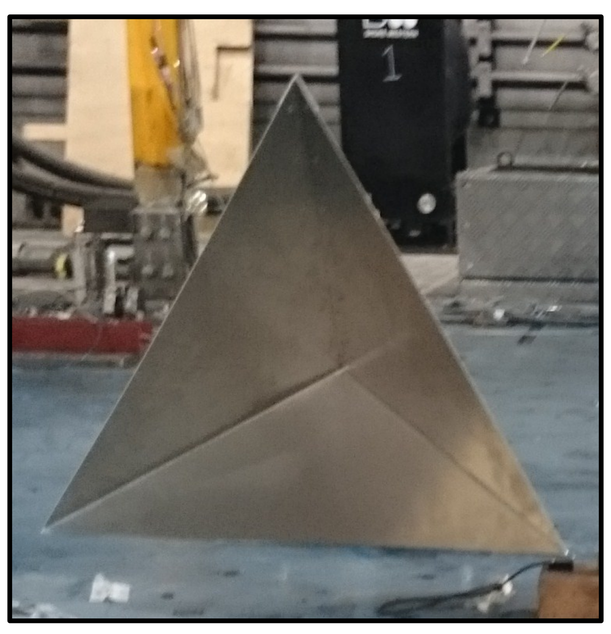


Figure 6
The corner reflector used in experimentation

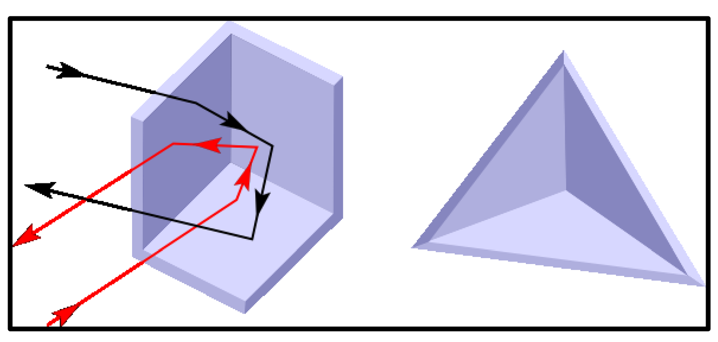
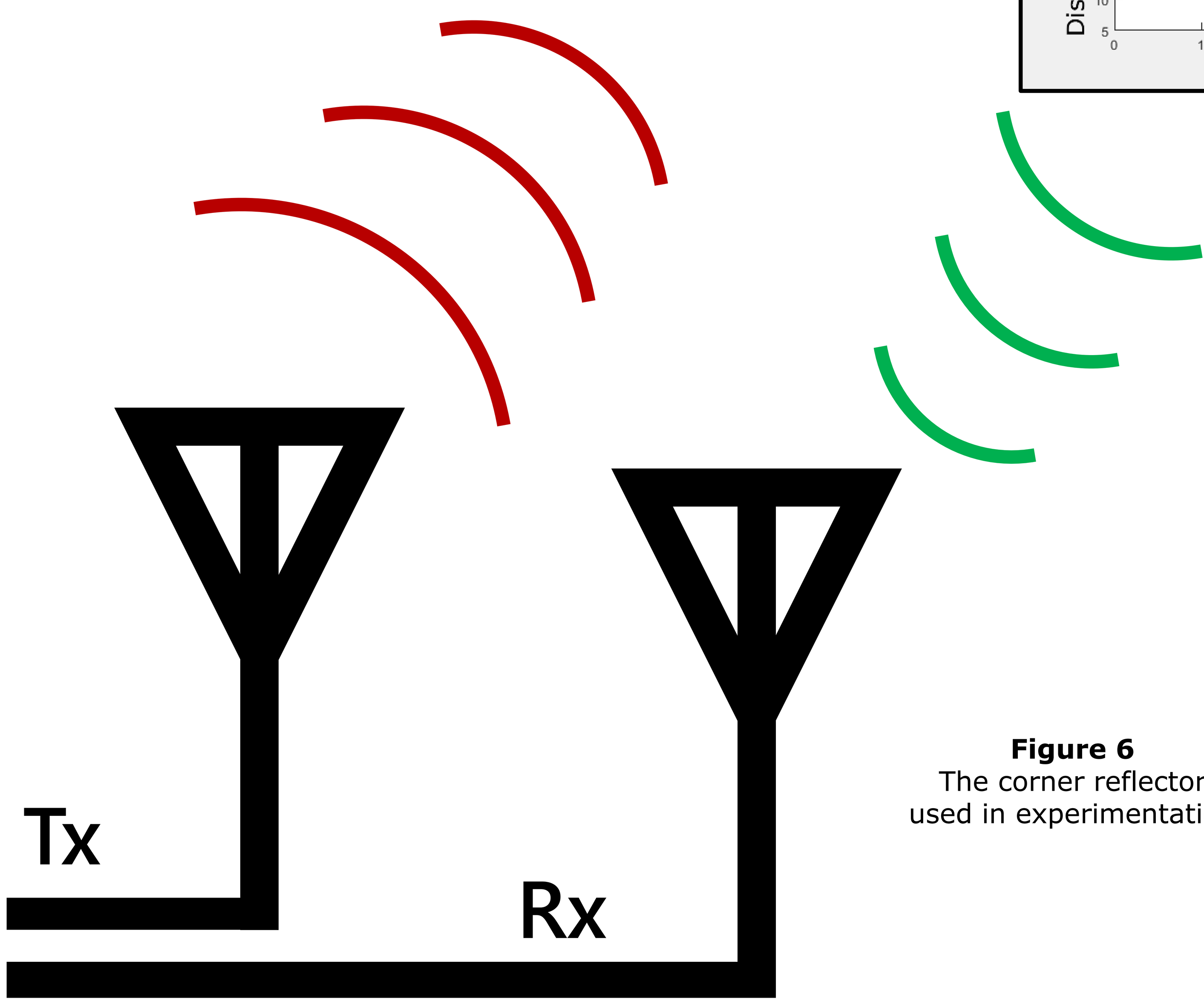


Figure 7
The reflection paths of waves incident on corner reflectors



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