Handy Microwave Sensor for Remote Detection of Structural Vibration

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ABSTRACT

The authors propose a novel handy microwave sensor for monitoring structures as bridges, towers, streetlight, floors. It operated at distance by detecting the natural frequency of the structure under test. The device has been designed as a handy instrument with a friend user-interface and a simple measurement procedure. The aim is to provide a portable equipment for the engineering studies. The prototype has been tested in laboratory conditions and in a preliminary in-field measurement session on a streetlight.

KEYWORDS : *radar, microwave, remote monitoring, structural health monitoring, Bluetooth*

INTRODUCTION

Radar interferometry is an increasingly popular technique for dynamic monitoring civil infrastructures. Its unique advantages are fast deployment and the capability to operate at distance. In 2004, Pieraccini et al. [1] designed and tested in field the first interferometric radar for dynamic monitoring of bridges, now many research groups, professionals, and companies have tested it in different operative scenarios [2]: bridges [3, 4], bell-towers [5, 6 ,7], wind towers [8, 9, 10], stay cables [11], industrial chimneys [12], guyed must [13], culverts [14], buildings [15, 16, 17], monumental buildings [18], canopies [19].
Nevertheless, the current equipment is rather bulky and expensive. Typically a radar head weight 15-20 kg and the cost overcomes 50000 €.
The aim of this paper is testing a different approach to radar interferometry. Technological solutions have been specially selected and implemented with regards on cost and weight. The goal is a device that can be brought with a single hand, installed on a light tripod for camera, and wireless controlled by a tablet.

1 WORKING PRINCIPLE OF RADAR INTERFEROMETRY

An interferometric microwave sensor is able to detect differential displacements of the targets in its cone of view by exploiting the phase information φ of the backreflected microwave signal as sketched in Figure 1.
Indeed

$$\varphi = \frac{2\pi}{\lambda} R(t) \tag{1}$$

with R distance from the target and the sensor, λ wavelength. Unfortunately, the phase information cannot be exploited directly for distance measurement, as it is affected by an ambiguity equal to half a wavelength (i.e., distances that differ by a multiple of a half a wavelength give the same detected phase), but if the target moves of a fraction of wavelength, the differential displacement can be detected as a phase shift with a precision depending on the capability of the electronic device to appreciate small phase rotation.

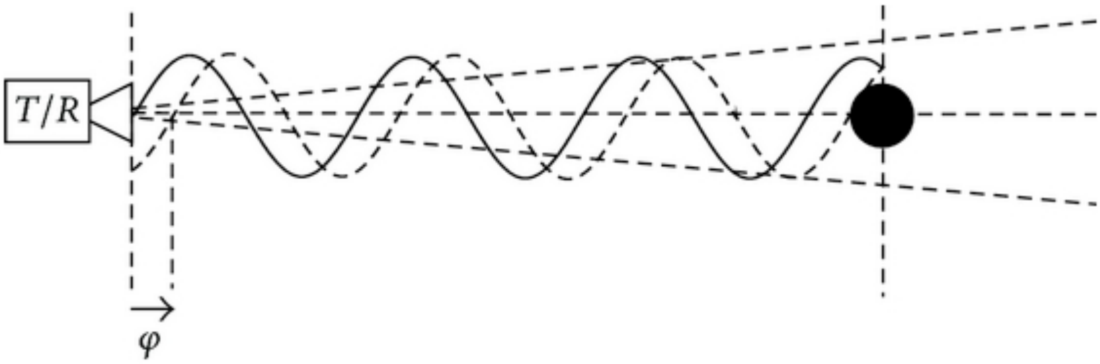

Figure 1: Working principle of interferometry

The FFT of the unwrapped phase provides directly the vibration spectrum of the target under test. As it is well known, this is the key parameter in dynamic monitoring of large structures, as bridges, towers, buildings and so on [20, 21, 22].

2 THE SENSOR

The sensor that has been developed is a miniaturized X-band radar. It generates a continuous wave signal at 10.525 GHz by using a microwave oscillator and a patch antenna. A receiving antenna and a double balanced mixer extracts the phase modulation given by the movement of the target. The signal is then amplified and filtered with low pass Butterworth filter with cut-off frequency of 200 Hz. Analog to digital conversion for post process analysis is provided by an 8-bit analog to digital converter with minimum sample rate of 2 kS/s. A tablet controls the radar through a Bluetooth link. An Android app gives the start and the end of measurement, it saves the acquired data, it calculates the FFT and plots the result. A more advanced processing has been implemented with a Matlab GUI, which provides the targets displacement with respect its equilibrium position and its oscillation frequency.

3 LABORATORY TEST

With the aim to evaluate the sensor in controlled conditions, a first test has been arranged in laboratory. A 1.3 m aluminium rod with 3 cm x 1 cm rectangular section has been used as target. Its oscillation frequency is given by [23, 24], equation (2):

$$f_0 = \frac{1.875^2}{2\pi}\sqrt{\frac{E \cdot I}{\rho \cdot A \cdot l^4}} \tag{2}$$

$$I = \frac{b \cdot h^3}{12} \tag{3}$$

Aluminium density is $\varrho=2700$ kg/m^3, its Young modulus is $E=70 \cdot 10^9$ N/m^2. A and l are the rod section and length respectively. Substituting in the equation the calculated frequency is 4.86 Hz.
As a further validation of the method, a seismic accelerometer (model: PCB 393B31) was fixed at the base of the rod. The complete experimental setup is sketched in Figure 2.

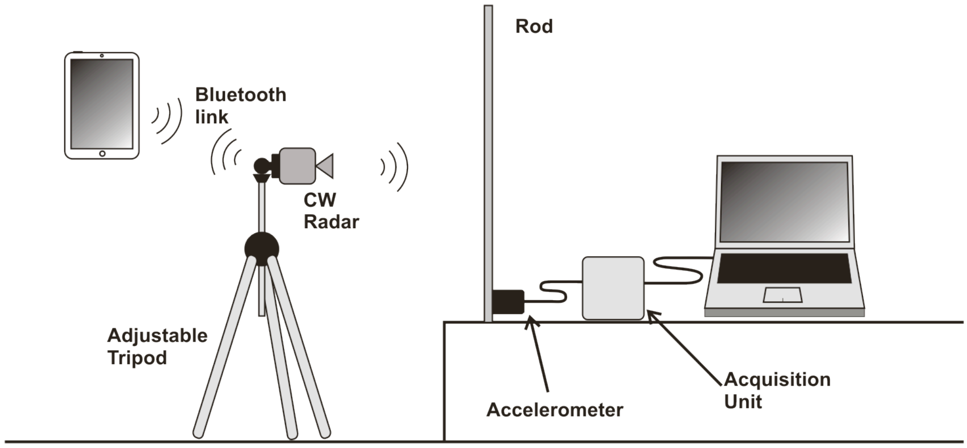

Figure 2: Experimental setup for rod oscillation measurement

The radar was placed at about 1 m in front of the rod. Figure 3 shows the comparison between the frequency analysis of the radar and accelerometer data for 40 s of acquisition, evidencing a full agreement and confirming the effectiveness of the radar. The main frequency peak has been detected at 4.77 Hz.

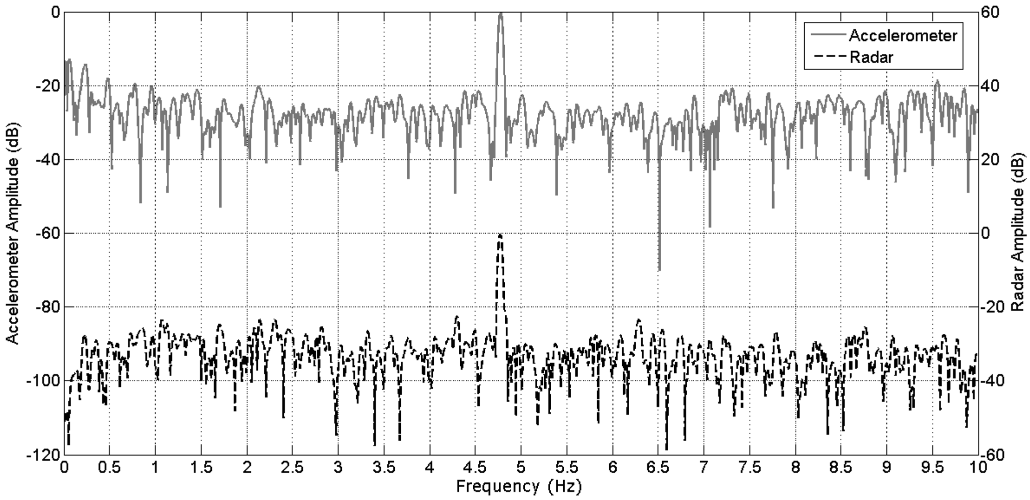

Figure 3: Rod analysis. Comparison between 40 s of accelerometric and radar data

4 IN-FIELD TEST

The laboratory test demonstrated the sensor ability to detect the frequency of a vibrating structure, nevertheless it is important to carry out an in-field test and possibly using an instrumented real structure. A common streetlight is chosen as test sample. The Figure 4 sketches the experimental setup. The radar points the streetlight horizontally, thus the backscattered and received signal is maximum. The height or radar haead and the distance from the streetlight are 1.7 m and 1 m respectively. The radar head was mounted on a tripod for camera. An accelerometer (the same of the previous test) was fixed at the same height pointed by the radar. With this approach the radar and the accelerometer should measure the same oscillation amplitude. The streetlight should not be stimulated by the operator because its oscillation is given by the wind and traffic. As in the previous case the two measurements are synchronous, and the acquisition time is 40 s.

Figure 5 shows the frequency domain analysis of the acquired signal. The agreement between accelerometric data and radar data is remarkable. Given the structure asymmetry it is reasonable to see two fundamental modes of vibration.

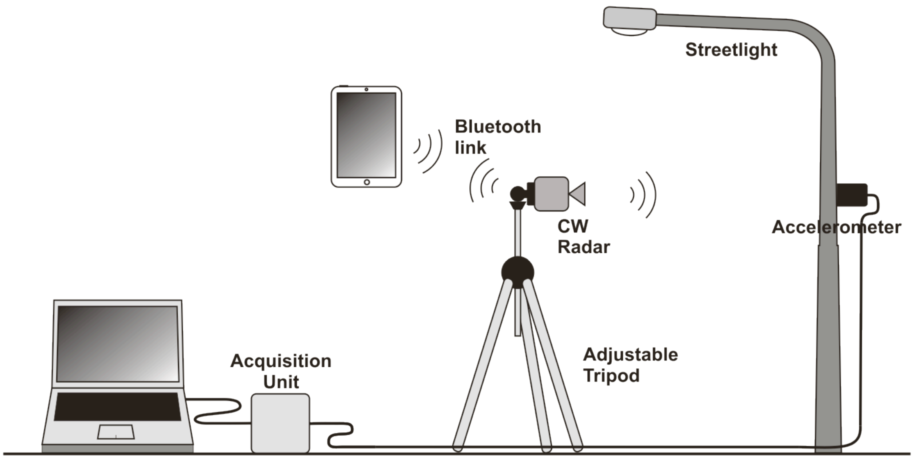

Figure 4: experimental setup for street light oscillation measurement

These frequencies have been detected by both sensors and correspond at 0.93 Hz and 2.22 Hz respectively.
It is of interest to note the signal to noise ratio (*SNR*) of accelerometric data and radar data. Despite the accelerometer was a high sensitivity instrument (10 V/g), the measurement shows on both frequencies a comparable *SNR*.

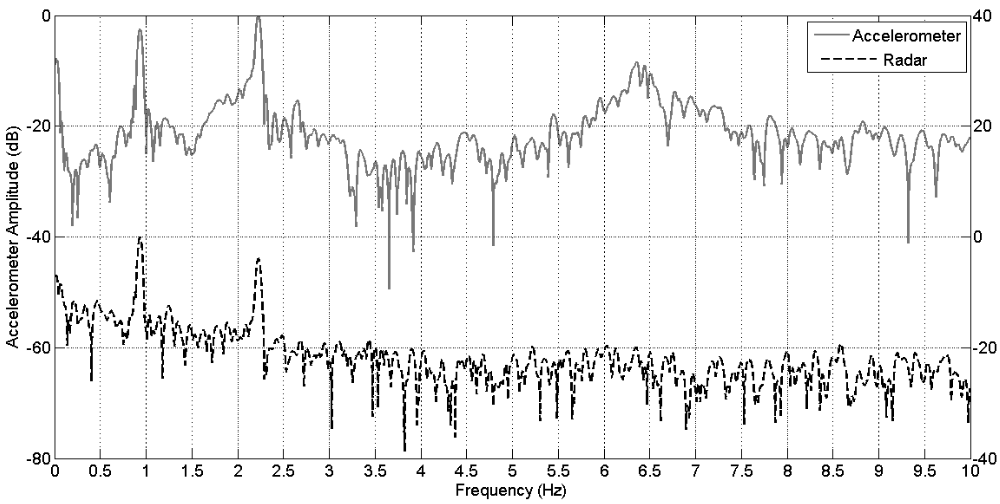

Figure 5: Street light analysis. Comparison between 40 s of accelerometric and radar data

CONCLUSION

A portable instrument for detecting the oscillation frequency of large structures has been designed and tested both in laboratory conditions and in-field on a streetlight. It has been demonstrated effective and accurate. Its measurement results are in full agreement with data of a high precision accelerometer used as reference.

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