Development of a novel radar sensor for monitoring the vibration characteristics of structures at short ranges

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Abstract. The capability of radar interferometry to monitor the vibration characteristics of different civil structures has been consolidating in the last decade and successful case studies have been issued by different research teams. In this paper the authors describe the development of a novel sensor working at a higher frequency with respect to system available from the market, and with a larger radiofrequency bandwidth, able to provide an improved range resolution. Measurement tests aimed at validating the observations carried out with the new sensors, and comparing the new prototype with a commercial instrument are discussed.

Keywords. Radar, Interferometry, Vibrations

1 Introduction

The interferometric Real-Aperture-Radar (RAR) technique for monitoring large civil engineering structures was introduced at the end of the 1990's (Farrar et al. 1999) and, as an operational tool and widely adopted, in more recent years (Pieraccini et al., 2004; Gentile & Bernardini, 2010; Beben et al., 2011; Negulescu et al., 2012; Luzi et al. 2012; Stabile et al., 2013). The main advantages of this non-contact technique include the capability to simultaneously estimate the displacement of different parts of the investigated structures, from remote, and with high accuracy and repeatability. The majority of the results discussed in literature are based on data collected through a well-known commercial apparatus: a continuous wave step frequency radar system working at Ku band (centre frequency: 17 GHz): the Ibis-S by IDS spa company (Coppi et al., 2010). The range resolution of this apparatus is limited to 0.5-0.75 m (depending on the countries), due to regulations on spectrum management and frequency allocation. In this paper the authors describe the preliminary test of a novel sensor working at a higher frequency, and with a larger radiofrequency bandwidth, able to provide an improved range resolution. In the test the result of the novel sensor are compared with the above commercial instrument. The core of the proposed system is an off-the-shelf, linear frequency modulated K-band (centre frequency: 24 GHz) sensor, with a lower maximum operating range with respect to the commercial interferometer, but whose development and implementation costs are drastically reduced. Other authors have recently investigated the application of similar sensors in the Structural Health Monitoring (Grazzini et al., 2009; Chunlong et al., 2015; Papi et al., 2014). Although the authors refer to a specific device, similar sensors are available from several companies: the performances here discussed are generally not linked to the choice of the used product. This novel sensor is devoted to a proof-of-concept trying to tackle operative aspects.

2 The technique

2.1 The functioning principle

A radar uses the time elapsed between the transmitting and the receiving of an electromagnetic waveform to locate targets included in the illuminated area, and reflecting the radiation with sufficient strength to provide a sufficient signal to noise ratio. The output from the radar survey is a 1D range profile, the range profile, where different peaks correspond to contributions coming from targets located at different distances. When different targets are present, the radar is able to provide their displacement history using specific waveforms

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sweeping a finite band, B, composed of different frequencies. Usually radar based on Frequency Modulated Continuous Wave (FMCW) or Step Frequency Continuous Wave (SFCW), instead of the standard pulse radio radar, are used to assure coherent signals (Skolnik, 1990) and a capability of sub-meter range resolution.

If the radar is coherent, also a phase value can be associated to the response of each target, and the minimum measurable displacement is of the order of small fractions of the transmitted wavelength. The range resolution ΔR, is defined as the minimum distance between two targets along the LOS at which they can still be detected individually. The characteristics of the used antennas, determine the size of the monitored scenario and the elementary sampling volume of a radar measurement, usually called radar bin.

The use of an interferometric radar to detect the vibration of an object is based on the capability of a coherent radar working at microwave frequency, to measure temporal range variations of the differential phase of the received echo with respect to the transmitted signal. Remembering that the wavelength in vacuum, λ, and the central frequency, f, of the swept band are related by equation (1):

$$\lambda = \frac{c}{f} \qquad (1)$$

where c is the speed of light. A higher operating frequency means in general a higher sensitivity to displacement variation.

Considering that presently available apparatus use a wavelength of the order of two centimeters, we can appreciate variations down to tens of microns. The vibration is seen by the radar as a range variation between the radar and the vibrating objects: in Figure 1 a simple scheme is depicted in the case where a single target is monitored. In this case the simple relationship between the measured differential phase and the displacement d occurred along the LOS is expressed by the following equation (2).

$$d = \frac{4\pi}{\lambda} \Delta\varphi \qquad (2)$$

The achievable accuracy is mainly dictated by the signal to noise ratio of the acquisition, which depends on the intensity of the reflected signal. According to the radar equation (Skolnik, 1990), the intensity of the received radar signal, is affected by the radar reflecting properties of a target, the transmitted power, the distance, geometric factors (shape and orientation) and finally dielectric characteristics of the target: a discussion about some of these issues can be found for example in Coppi et al. (2010), Luzi et al. (2012) and Chunlong et al. (2015).

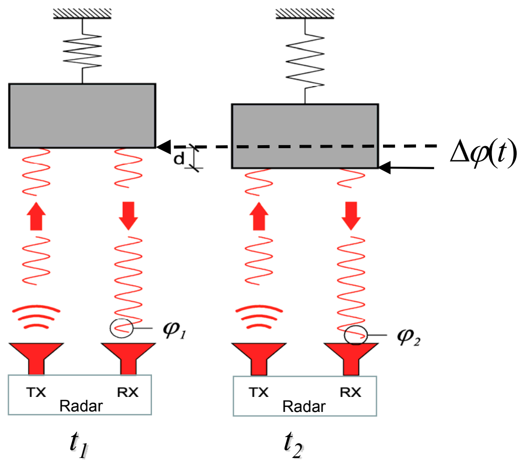

Fig. 1: Functioning principle of radar interferometry for displacement/vibration measurement. The target moves along the radar LOS inducing a variation vs time of the measured interferometric phase.

2.2 The FMCW radar

The radar sensor used in this test is a FMCW radar. This type of radar differs from those based on pulse in that the electromagnetic waves are continuously transmitted and the signal information is obtained varying its frequency and not its amplitude as in the pulse radar case. The frequency, of this signal changes over time, generally in a sweep across a set bandwidth. The frequency of the transmitted signal changes linearly over time as:

$$f_{RF} = f_0 + k_f \cdot t \qquad 0 \le t \le T \qquad (3)$$

where f_0 is the starting frequency, T is the time elapsed for sweeping the entire bandwidth B:

$$B = f_0 + k_f \cdot T \qquad (4)$$

and k_f is the sweep rate:

$$k_f = \frac{B}{T} \qquad (5)$$

The delay caused by the round-trip from the transmitting antenna to the reflector located at distance, d, is:

$$\Delta t = 2\frac{d}{c} \qquad (6)$$

where c is the speed of light.

The frequency of the signal received after a lapse Δt will be:

$$f_{REC} = f_0 + k_f \cdot (t - \Delta t) \quad \Delta t \le t \le T + \Delta t \qquad (7)$$

If we compare the transmitted and received signal, mixing them through a basic homodyne receiver configuration shown in Figure 2, we obtain the difference in frequency, Δf, between the transmitted and received signal, which is proportional to the delay Δt:

$$\Delta f = k_f \cdot \Delta t \qquad (8)$$

This intermediate frequency signal *Δf*, which can be associated to the distance, ranges in the low frequency band (audio frequency), and can be easily acquired and processed. In Figure 3 the basic scheme of the use of a linear frequency modulation to measure the round-trip of the reflected signal is shown.

The relationship between Δf and the distance d can be obtained rearranging eq. (6) and (8):

$$\Delta f = \frac{B}{T} \cdot 2 \cdot \frac{d}{c} \qquad (9)$$

A real case, as the monitoring of a civil structures, is of course represented by a scenario where different targets are present (e.g. the different parts of a building or a bridge which are located at different distances).

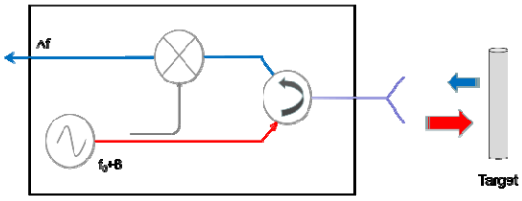

Fig. 2 Scheme of a typical homodyne configuration providing the intermediate frequency signal Δf. The oscillator sends the generated signal to the antenna and to the mixer.

Their distances will correspond to different frequencies. The resulting IF signal contains superposition of the individual signals from each target. Using the Fourier Transform we can obtain a range profile of the monitored scenario and to separate the single targets we need a range resolution, Δd, which will be associated to the FT frequency resolution, Δf. We take Δf=1/T (the sampling duration T+Δt can be approximated as T, considering that Δt<<T) we can now calculate Δd using eq. (9):

$$\Delta f = \frac{1}{T} = \frac{B}{T} \cdot 2 \cdot \frac{\Delta d}{c} \qquad (10)$$

and finally:

$$\Delta d = \frac{c}{2B} \qquad (11)$$

showing that the range measurement resolution is only limited by the sweep bandwidth B.

The transceiver used in this test is marketed by Sivers IMA AB (Sweden). Its main characteristics are resumed in Table 1. In particular the operating frequency is higher than that one of the Ibis-S radar sensor. Also its maximum bandwidth is larger, 1500 MHz with respect to the 300 MHz of Ibis-S; this allows achieving a nominal range resolution of 10 cm. As far as the maximum range is concerned, a comparison, based on the available data cannot be carried out data, but the higher emitted power and antenna gain of Ibis-S makes the Ibis-S capable to monitor structure up to 1000 m distant (Luzi et al., 2013); similar value are not possible using the new sensor in the actual configuration.

Table 1. Sivers IMA radar sensor characteristics.

Parameter	
Centre frequency (GHz)	24.75
Bandwidth (MHz)	1500
Antenna gain (dB)	20
Antenna Field of View (°) H	18.6
Antenna Field of View (°) E	16.1

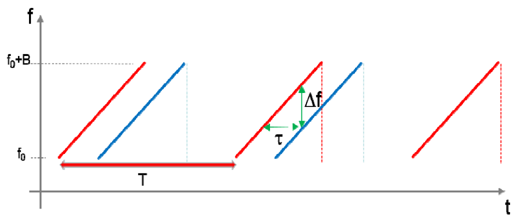

Fig. 3 Scheme of the FMCW modulation used in radar technology to retrieve the round-trip time lapse between the radar and the target.

As usual for radar measurements, the maximum available range of the system is limited by the sensitivity of the detector, the transmitted power, and the sampling rate of the ADC. Details about the tested device are given in the following section.

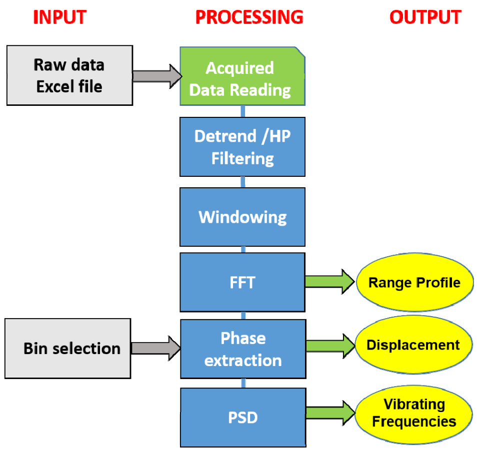

Fig. 4 Block diagram of the processing procedure applied to the received raw radar data

2.3 The data processing

The data acquired through the radar are processed in two steps: the one necessary to transform the FMCW data to a range profile, based on a Fourier Transform and including possible windowing, and the second one the extraction of the phase temporal series and their spectral analysis calculating the power spectral density (PSD) (Welch, 1967). In Figure 4 a block diagram of the whole procedure is depicted.

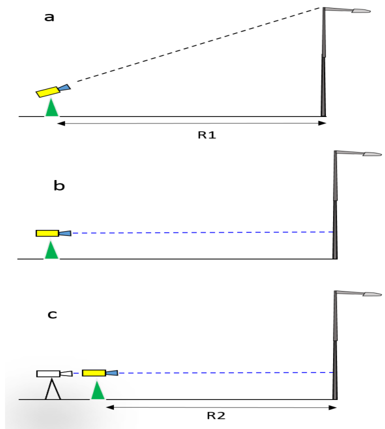

Fig. 5 Schematic of the three different setups of the test and picture of the light pole

The sampling frequency of the displacement signal is 3.2 Hz a value low with respect to that available from Ibis-S, but sufficient for this preliminary test focused on the monitoring of a target with vibration frequency lower than the corresponding Nyquist frequency (1.65 Hz). In any case this preliminary test is aimed at underlining the capability of a FMCW working at a higher frequency and wider band with respect to the available apparatus.

3 Experimental results

3.1 Test description

To verify the capability of the proposed sensor as a remote vibration monitoring tool, a simple experiment was carried out. A light pole 8 meter high, only solicited by the wind and the ambient noise, was observed from two different distances of 6.8 m and 7.3 m with two different angles, as resumed in Figure 5, to detect its natural oscillating frequencies. The pole has a “L” shape. The object was previously monitored through a Ku band radar interferometer frequently used in literature, the Ibis-S marketed by IDS spa. The range profile shown in Figure 6 was obtained with the new sensor in the first position, a, with the observation direction of the antenna inclined of 42º and a distance between the radar and the pole of 7.3m. To support the interpretation a scheme indicating the location of three main peaks is depicted as Figure 6.

Considering that each bin corresponds to 10 cm, the estimated position of the pole at bin 73, is correct.

Two further acquisitions were aimed at confirming this decimetric range resolution. The sensor was oriented horizontally and two acquisitions with a relative change of the distance of 0.4 cm. The result of the range profile shown in Figure 7 confirms that each bin step corresponds to a 10 cm increment. Considering that the nominal range resolution of the available Ibis-S apparatus is 50 cm, there is a significant improvement.

2.2 Analysis of the displacement samples

First we have a look at the displacement histories retrieved from the radar measurements. In Figure 8 the temporal variation of the displacement for two different bins, 74 and 79, is shown. The amplitude ranges within ± 1 millimeter in both cases. The high spatial details provided by the decimetric range resolution, allow detecting the vibration frequencies of different parts of the pole. Calculating the PSD of the two different bins, 74 and 95 a clear peak centered at 1.518 Hz is detectable, see Figure 9.

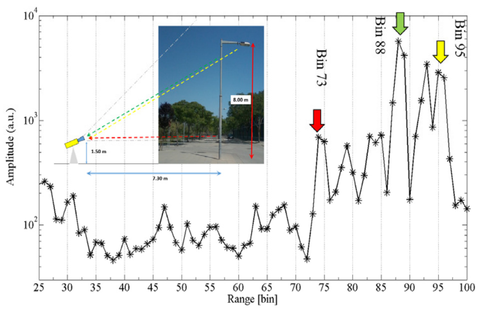

Fig. 6 Range profile obtained with the new sensor in configuration a (Table 2) and simple interpretation of the main radar echoes.

Table 2. Measurement configuration (ref. to Fig. 4).

Setup	A	b	c
Azimuth angle (º)	0	0	0
Elevation angle (º)	42	0	0
Distance Radar-target (m)	7.3	7.3	6.8

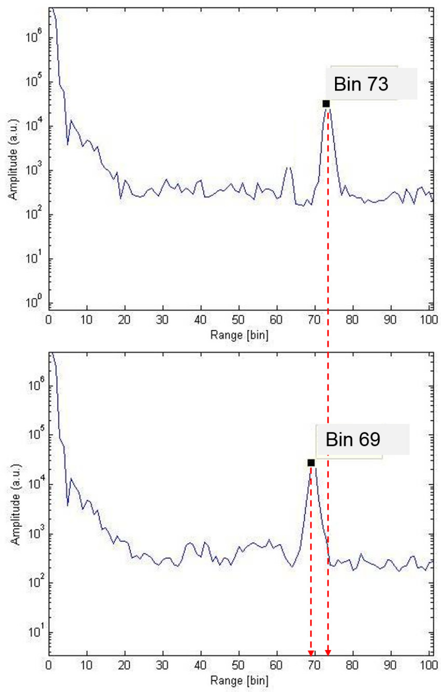

Fig. 7 Range profiles obtained moving the position of the radar 40 cm backward: the location of the pole echo changes from bin 73 to bin 69.

These vales have been compared with the result obtained through data previously acquired with the commercial instrument, the Ibis-S. In Figure 10 the PSD obtained using this second system is shown. In this case the PSD has been obtained with a displacement sampled at a higher frequency, 100 Hz; only the lower portion of the spectral plot is shown for a better comparison with the data of Figure 9. The data are in a good agreement.

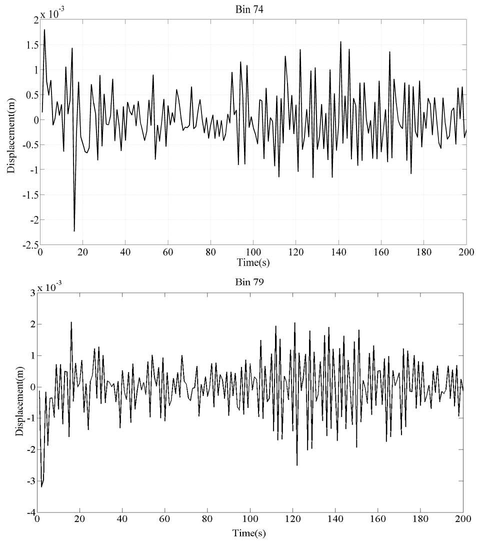

Fig. 8 Displacement samples corresponding to two different bins: 74 and 79.

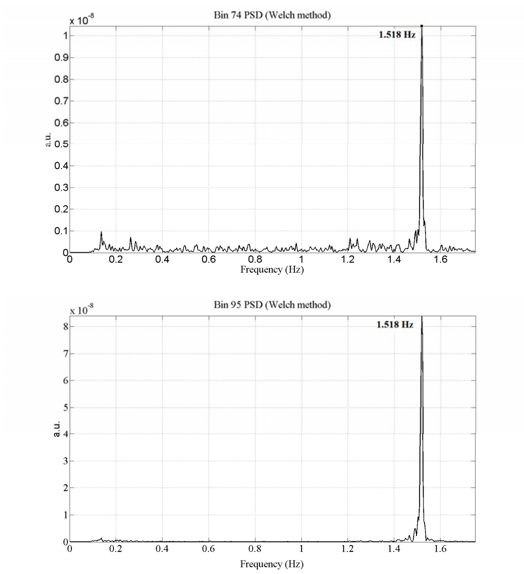

Fig. 9 PSD calculated for bin 74 and 95.

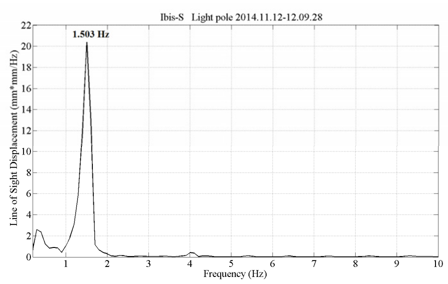

Fig. 10 PSD calculated from data acquired through Ibis-S system.

There is a small difference of the order of 0.01 Hz, which is attributable to the different duration of the displacement record.

3 Conclusions

On the bases of a simple experimental test, the main performances of a new FMCW sensor, working at K band (24 GHz), as a monitoring tool of mechanical vibration, have been analyzed. The improved range resolution, with respect to the presently available on the market apparatus has been demonstrated. The capability to detect the natural frequency of a light pole has been verified comparing the results of the novel sensor with those ones obtained through the Ibis-S system. Some limitations as the low sampling frequency and a lower maximum range have been highlighted. The analyzed sensor is very promising and deserves deeper studies and tests.

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