High-speed CW step-frequency coherent radar for dynamic monitoring of civil engineering structures

M. Pieraccini, M. Fratini, F. Parrini, G. Macaluso and C. Atzeni

A high-speed coherent radar for dynamic testing of civil engineering structures is proposed. The radar operates a continuous-wave (CW) step-frequency in Ku-band, and the base-band signal is generated by direct digital synthesis. Vibration measurements carried out on a 200 m-long bridge forced by vehicular traffic are reported.

Introduction: Monitoring of vibrations and transient displacements of civil engineering constructions such as buildings, bridges and towers is of paramount importance for early identification of structural problems and to enable remedial actions to be taken [1, 2]. Dynamic monitoring is currently implemented by contact sensors, such as networks of piezoelectric accelerometers or optical targets installed over the structure. Such sensors are accurate and reliable but need to be positioned in contact with the surveyed structure. They also provide information which is limited to the specific point of the sensor position, thus inhibiting the possibility of obtaining a continuous global map of the structure vibration.

Monitoring of large structures can give rise to accessibility problems, as it requires expensive scaffolding and a network for transmission of data to a remote collection station [2, 3]. Moreover, in a number of situations, placing of contact sensors may be not possible. This is the case, for example, in buildings with symptoms of impending collapse, after a seismic shock, a blast, or intentional damage. In such cases, remote sensing techniques able to scan the structure from a safe distance are required.

A coherent radar based on continuous-wave step-frequency (CWSF) operation has been recently proposed to image deformation maps of static displacements of a variety of structures, such as bridges [4] and buildings [5]. This radar, based on a phase-lock loop (PLL) microwave synthesiser, was however too slow to image dynamic displacements, such as steady-state or transient vibrations.

In this Letter, we describe the design and the application of a coherent Ku-band radar based on direct digital synthesis (DDS) able to acquire synthetic radar images at 20 Hz repetition rate, thus allowing the natural or forced vibrations of civil engineering structures to be followed. The radar dynamic imaging capability has been demonstrated by monitoring the vibrations of a steel bridge forced by vehicular traffic.

Radar: A CW-SF radar synthesises a large bandwidth B by transmitting a number N of single tones at uniform step Δf. Range resolution Δr and unambiguous range R_ν are given by the following equations [4]:

\[ \Delta r = \frac{c}{2B} \]  
\[ R_\nu = \frac{c}{2\Delta f} \]

with c being speed of light.

A practical rule of thumb is to set the unambiguous range at about twice the distance of the farthest target that can be detected. A 0.5 m range resolution and a 1 km unambiguous range, meeting the imaging requirements of the most part of civil engineering structures, thus require a bandwidth larger than 300 MHz scanned in about 2000 steps. A suitable repetition rate for following the typical dynamic oscillations of the structures of interest should be faster than 20 Hz.

The radar is continuously operated and repeatedly scans the bandwidth with incremental frequencies. Once the complex (i.e. in phase and quadrature components) echo signals have been received for each step frequency, the time domain image of the target is obtained by performing their IFFT. As the phase of each image pixel is determined by its distance R from the radar, a displacement (dR) of the pixel along the range direction in two successive images can be obtained from the corresponding pixel phase shift (\( \phi \)) according to the relationship

\[ dR = \frac{c}{4\Delta f} \phi \]

with \( c \) as the band centre frequency. Therefore, according to known coherent processing [5], the instantaneous displacement map of the illuminated target can be obtained from the argument of the complex conjugate product of two radar images.

It is to be noted from (3) that sensitivity of the displacement measurement is increased for a higher central frequency. Furthermore, target reflectivity increases with the frequency as well. Therefore, a suitable microwave centre frequency for imaging large structures and for detecting millimetric displacements should be higher than 10 GHz. However, the maximum unambiguous displacement is equal to half-a-wavelength, so it decreases with the frequency. A 16.8 GHz centre frequency was thus chosen as a good practical trade-off.

The most popular architecture for coherent radars is based on the PLL. Commercially available PLL synthesisers however are not fast enough to meet the above specification on the scan rate, whereas the typical hopping speed of a DDS is largely suitable. Fig. 1 sketches the block scheme of the constructed DDS-based radar architecture. The DDS device generates a tunable sinewave through a high-speed D/A converter that reads a sine lookup table in response to a digital tuning word and a fixed-frequency precision 300 MHz clock source [6]. As the output signal is sampled, the spectrum contains multiple images of the fundamental synthesised frequency. A dual helix filter selects the fifth image in the 830–850 MHz band. A comb generator multiplies this band by 20. The filtered output signal is provided to a power amplifier (PA) that transmits in the 16.6–17.0 GHz band. The receiver channel is based on a standard homodyne architecture. Design specifications on phase accuracy are suitable for measuring short-term displacements with a range accuracy better than 0.1 mm.

**Fig. 1 Block diagram of radar system**

**Fig. 2 Measurement geometry and instantaneous displacements of first and second vibrational modes**

- **a** Measurement geometry
- **b** Instantaneous displacements of first and second vibrational modes
- (i) and (ii) are extremal elongations of first mode; (iii) and (iv) are extremal elongations of second mode

**Experimental results:** To test the radar equipment a measurement campaign was scheduled to survey the vibrations of a single-arcade 200 m-long bridge crossing the river Arno in Florence (Italy). It consists of a stayed unanchored bridge with deck in stiffened steel, the vibration of which was forced by heavy vehicular traffic. The radar was positioned at the base of one of the bridge pillars (Fig. 2a), and acquired continuous measurements of 5 to 6 min duration at 20 Hz rate. Table 1 summarises the setup measurement parameters. By processing pairs of complex images pixel by pixel, the range displacement is obtained from (3), and the effective vertical displacement (\( \Delta z \)) was calculated as a projection along the vertical axis. Fig. 3 shows the FFT of the displacement at the centre of
the bridge: the natural frequency of the bridge is evident at about 0.6 Hz. The frequencies of higher-order vibrational modes are clearly detected as well.

Table 1: CW SF radar parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<tbody>
<tr>
<td>Transmitted power</td>
<td>30 dBm</td>
</tr>
<tr>
<td>Central frequency (f_c)</td>
<td>16.8 GHz</td>
</tr>
<tr>
<td>Bandwidth (B)</td>
<td>400 MHz</td>
</tr>
<tr>
<td>Frequencies number (N)</td>
<td>5120</td>
</tr>
<tr>
<td>Frequency step duration</td>
<td>10 μs</td>
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<tr>
<td>Sample number per tone</td>
<td>2</td>
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</table>

Fig. 2b shows the measured modal displacements at the first (0.6 Hz) and the second (1.2 Hz) natural frequencies. Of note is the typical shape with a central knot of the second vibrational mode. These displacements were obtained by filtering the band of interest with a 0.3 Hz wide rectangular filter. Furthermore, the range displacement plot was filtered by using a 25 m wide Hamming filter.

**Conclusion:** The described coherent radar system appears to be a powerful and versatile instrument for dynamic testing and/or monitoring of civil engineering structures. The radar, remotely operating, provides effective maps of the structural displacements. As it is able to image the structure in less than 50 ms, it can detect the fastest movement consistent with an architectural structure excited by external causes; such as wind or vehicular traffic, or artificial ones such as a vibrodyne. Furthermore, the equipment is portable and can be rapidly installed and operated, thus resulting as suitable for fast monitoring even in emergency situations.