STRUCTURAL HEALTH MONITORING WITH 94 GHz RADAR

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ABSTRACT

Technological developments in low-power mmW radar allow the measurement of deformations in the order of few micrometers and monitoring dynamic processes like structural vibration. This paper presents a fast acquisition FMCW radar operating at 94 GHz and recent experimental results of remote observation of micrometric vibration motion for bridge structural health monitoring. The presented approach offers cost reduction and applicability advantages compared to conventional techniques.

Index Terms— mmW Radar, Structural Monitoring, Radar Surveying, Radar Biological Signatures

1. INTRODUCTION

The high sensitivity of radar echo phase with range changes is exploited in multiple deformation monitoring applications of radar remote sensing with typical precisions in the order of centimeters to millimeters [1,2]. Simple Continuous Wave (CW) radars can obtain useful dynamic information using micro-Doppler techniques [3] on simple scenarios with a dominant scattering center. In complex environments like natural or urban scenes a high spatial resolution is desirable to discriminate among multiple scattering centers. Cost-effective solutions are based on linear FM generation in the transmitter combined with homodyne de-ramping in the receiver [2]. In moderate dynamic situations, typical of large structures vibration, radar echo processing and interpretation is simplified by using a FM Sweep Repetition Frequency (SRF) well above the motion frequencies observed. In this way the over-sampling beyond the Nyquist limit associated to the scene dynamics can be used to increase the signal-to-noise ratio (SNR) by coherent integration. In very slow dynamics situations controlled radar motion can be added to form synthetic apertures providing cross-range resolution and better scattering centers discrimination [2]. Short range frequency-modulated continuous-wave (FMCW) radars are suitable sensors for bridges and highways monitoring. These infrastructures deteriorate with time due to environmental reasons, fatigue caused by traffic loads and extreme conditions such as earthquake events. For safety reasons periodical inspections and controls of bridges and highways are required [5]. Traditional methods are based on visual inspections which may miss early signs of degradation. An alternative technique is vibration-based structural health monitoring, in which changes in the physical characteristics of the structure like mass, stiffness and damping will affect the measured vibrational parameters. Most studies are being carried out using local sensors such as accelerometers or high precision GPS [5,6]. As opposed to in-situ measurements, short-range radars can be used for remote sensing of vibration parameters of structures which may be convenient to speed-up data-acquisition without disturbing traffic. The amplitudes of high frequency resonant modes of vibration can be very small, in the order of micrometers. Thus, the measurement have to be based on the echo phase shifts. For this reason, very high frequencies of operation are desirable since every phase shift cycle of the echo corresponds to $\lambda/2$ in range change. The paper presents a 94 GHz radar developed for short range applications and an experimental evaluation of the remote vibration characteristics of a railway bridge.

2. 94 GHz FMCW RADAR

A 94 GHz FMCW radar has been developed [4] to assess applications in micrometric structural motion and biomedical signatures analysis. The system, shown in Fig. 1 is based on a homodyne configuration using a FM generation module based on a DDS (Direct Digital Synthesizer). Two frequency multiplication stages are used to achieve the W-Band operation as shown in system block diagram of Fig. 2. The basic radar parameters are:

Carrier Frequency	f_0 = 93.96 GHz
Transmitted Power	Pt = 10 dBm
FM sweep repetition freq.	SRF = 1.3732 kHz
Transmitted Chirp bandwidth	B = 1.512 GHz
Conical Horn Antennas Gain	Ga = 15 dB
Antennas Beamwidth	$\Delta\theta$ = 13 degrees
Noise factor	NF = 5.5 dB
Range resolution	ΔR = 10 cm

The SNR analysis of the range compressed echo signals obtained after Fast Fourier Transform of the down-converted received signal, reveals the capability of detecting small targets at ranges of hundreds of meters (Fig. 3)

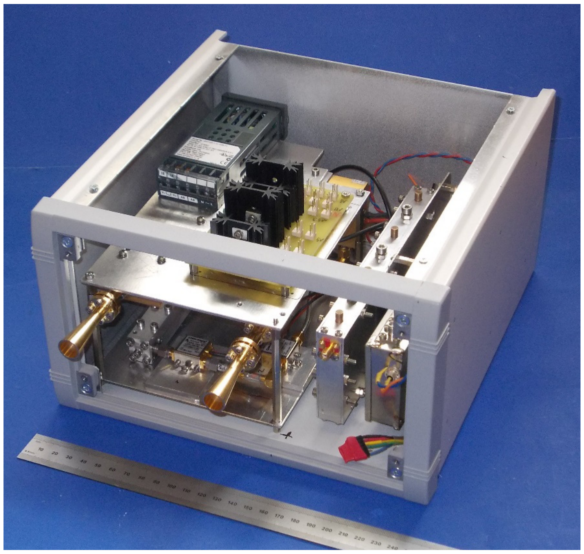

Fig. 1 FMCW research radar during integration phase

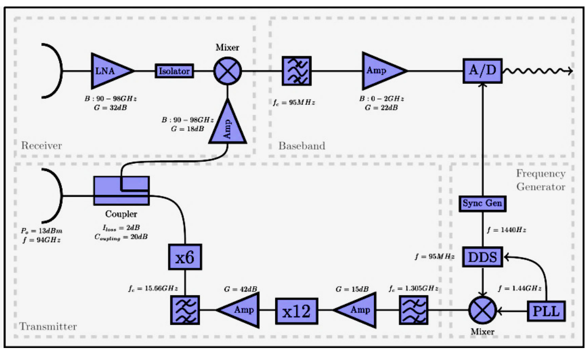

Fig. 2 FMCW radar block diagram

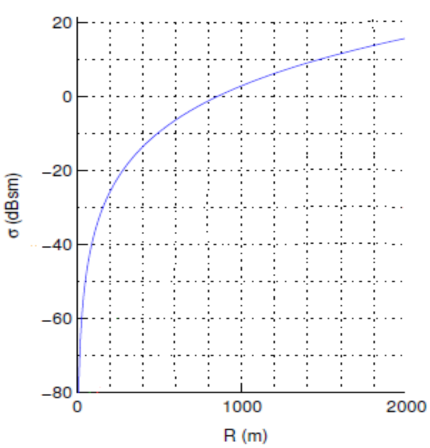

Fig. 3 Detectable Radar Cross-Section (RCS) in dBsm (for S/N_{min} = 10 dB) with respect to target range.

After warming up, the radar has excellent stability. The theoretical range resolution delivered by Fast Fourier Transform of post-mixer beating signals has been confirmed in anechoic chamber measurements. Controlled micrometric displacements of small metallic targets can be tracked with precisions in the order of 10 μm or better depending on the echo SNR [4].

3. BRIDGE DYNAMICS MONITORING

Conventional bridge deformation/vibration test and analysis are based on controlled loading and motion recording instrumentation based on a combination of accelerometers, geodetic-class GPS or optical survey equipment [4,5].
FMCW radar has also been used for real-time structural deformation sensing, achieving sub-millimetric precision when operating at W-Band (94 GHz) [4]. Fig. 4 shows a metallic structure railway bridge located in Monistrol de Montserrat (Catalunya). The suspended part of the bridge has a span length of approximately 45 m between columns. The deformation has been observed using the FMCW radar located at ground level near the bridge during the train passages. The deformation and vibration is obtained from the phase shift of the range compressed echoes corresponding to different scattering centers naturally created by the bridge metallic structure.

Fig. 4 Photograph of the rail bridge of Monistrol de Montserrat during a train transit during the radar data take. The red circle shows the radar location.

Fig. 5 presents the deformation of several scattering points of the bridge during a train transit. The bridge peak deformation due to train load was -7 mm with respect to the unloaded reference position in the radar slant looking direction. Note the higher elevation of the bridge section observed around 16-18 s due to leveraging effect of the train located past the bridge pillar. Since phase rotates 360 degrees for a $\lambda/2$ = 1.6 mm range change, the phase must be unwrapped to obtain the correct deformation. Typical bridge vibration frequencies are in the order of 2-10 Hz. Therefore the much faster radar SRF allowed to perform coherent integration and 10:1 decimation in the time axis without spectral aliasing nor losing details of the bridge motion.

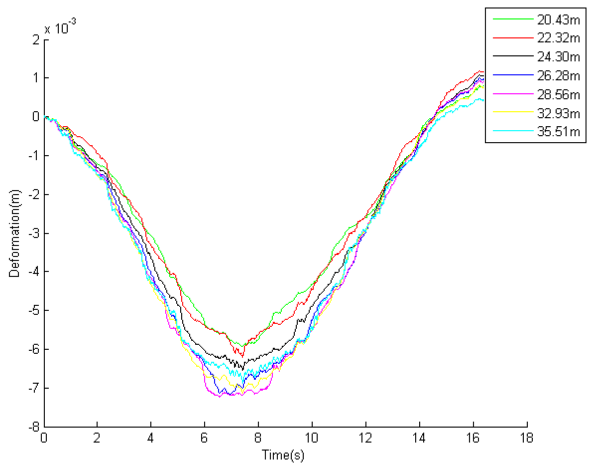

Fig. 5 Bridge deformation of selected scattering points ranging from 20 to 35 m from the radar location.

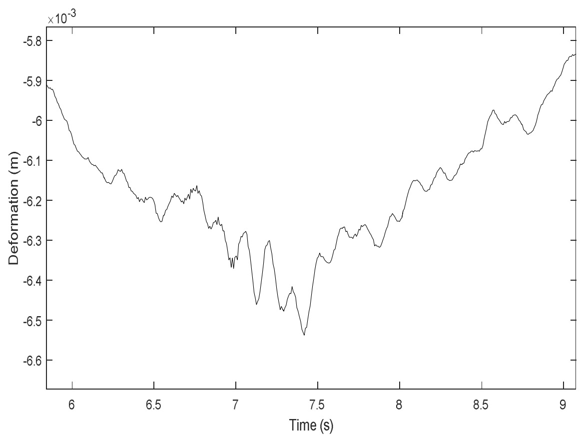

Fig. 6 Detail of the bridge deformation along time measured for a scattering point of the bridge located at 24.3 m from the radar. Deformation units are millimeters from the unloaded bridge reference position.

Note the clean deformation curve in Fig.6 with a residual noise in the order of 10 µm confirming the figure obtained in the radar indoor calibration/validation. The acquired data has been recently reprocessed to extract the natural bridge resonances and the effects of the train load on them.

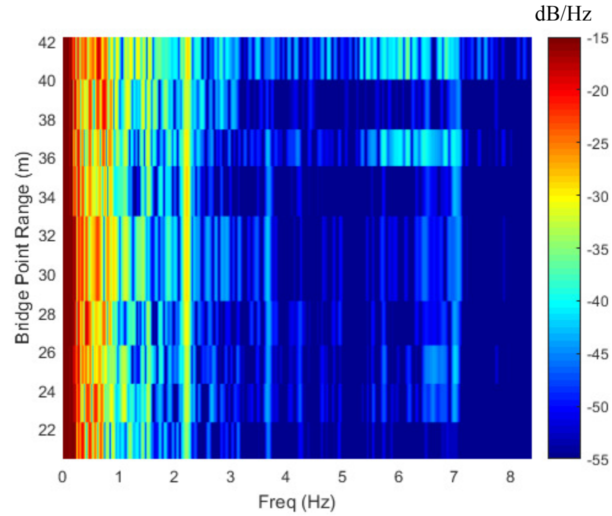

Fig. 7 Resonant bridge frequencies obtained from Fourier analysis of the deformation data at 10 bridge scattering centers located from 22 to 42 m away from the radar.

Fig. 7 shows a large DC component due to the bridge deformation when loaded and several resonance frequencies at 2.21, 3.65 and 7.03 Hz. Theoretically, the presence of a large mass over the bridge should have an impact in the sense of lowering the natural resonance frequencies of the bridge. To check this hypothesis a series of Short Time Fourier Transforms (STFT) have been carried out on different scattering positions of the bridge. Figs. 8 and 9 show the progressive downward shift of the resonance frequencies along time resulting from the train transit over the bridge as expected.

Using a simple vibration model the shift of different resonances with respect to unloaded frequency should be proportional to the resonance frequency center. This is confirmed by the results showing a larger change in the 7 Hz line. The amplitudes of Fig. 9 are larger than those shown in Fig. 8 because they correspond to a scattering point closer to the central part of the suspended bridge segment with larger oscillations. The STFT of every scattering point reveals also when and where the different vibration frequencies are better excited depending on the train location, rail discontinuities and wheel-rail friction.

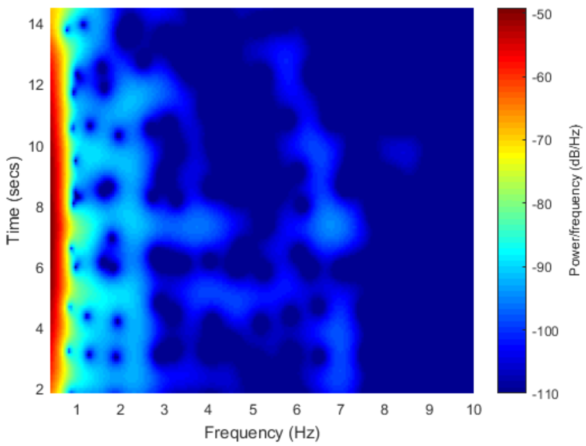

Fig. 8 STFT obtained by processing 512 overlapped samples from a total of 2250 deformation vs. time samples of a scattering center located at 22.3 m from radar.

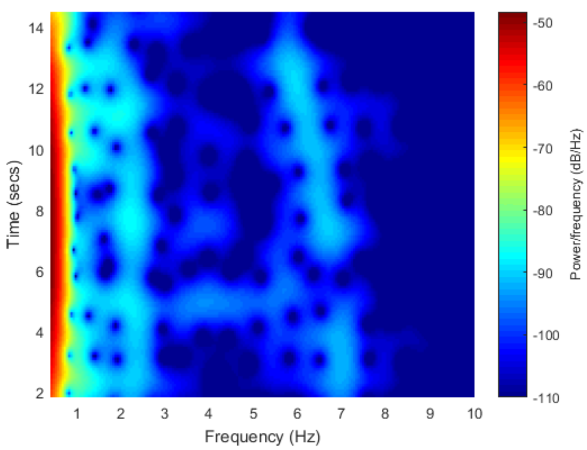

Fig. 9 STFT obtained by processing 512 overlapped samples from a total of 2250 deformation vs. time samples of a scattering center located at 35.5 m from the radar.

4. CONCLUSIONS

Millimeter wave radars are excellent candidates to remotely obtain structural health parameters of bridges and other infrastructures. Using near-by locations of opportunity and taking advantage of the motion created by usual traffic operation, bridge deformation spans, natural and loaded resonant frequencies and other parameters of interest can be easily obtained without installing local sensors or conditioning the infrastructure operation.

Acknowledgements

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