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Radar-based Mechanical Vibration Sensing for Structural Health Monitoring Applications: A Comparison of Radar Transceiver Measurements at 24 GHz and 100 GHz

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Abstract

Conventional strategies to measure mechanical vibrations from remote distance are based on Laser-Doppler-vibrometry (LDV). This technique is only rarely used in practical structural health monitoring (SHM) applications, due to the high costs of these devices. Radar technology represents a promising new approach towards in-situ SHM-scenarios with permanently installed sensors, because of the low costs of the radar-modules (only few Euros), the ability to measure mechanical vibrations behind barrier materials and the low attenuation which enables long distance measurements.

In this paper, we report on an experimental study with two radar transceivers at 24 GHz and 94.3 GHz for mechanical vibration sensing in SHM-applications. Interesting here is that the radar transceiver at 24 GHz has low costs and shows similar performance compared to a laboratory radar-transceiver system at 94.3 GHz. The low costs makes this kind of radar sensor extremely interesting for a variety of SHM-applications. Results will be demonstrated here for mechanical vibration sensing behind a barrier material, i.e. a polystyrol foam. This measurement could not be performed with an LDV-approach, because the laser beam is not able to penetrate the barrier material. Additional results are shown for damage detection and for harmonic oscillation measurements with a shaker system. This approach demonstrates the principle to sense mechanical vibrations at microwave- and millimeter-wave frequencies behind a barrier material.

1 INTRODUCTION

There are at least two operational modes for radar-based structural health monitoring systems: the first one is based on Doppler signatures for vibration sensing either in a continuous-wave (CW) [1], [2] or a frequency-modulated continuous wave (FM-CW) mode [3]. On the other hand, a broadband radar system with differential imaging capabilities can be used, where the differential image is calculated between measurements from the pristine and the damaged state of the structure. This methodology has been demonstrated for glass-fiber reinforced materials of wind turbine blades in [4], [5].

Radar-based SHM methodologies have a variety of interesting features [1]:

- The short wavelength enables mechanical oscillations measurements with small vibration amplitudes in the µm-range with high fidelty.
- Vibration sensing is performed in a non-contact way, similar to Laser-Doppler vibrometry, with good signal-to-noise ratio.
- Most non-conductive materials are transparent at these frequencies so that mechanical oscillations of buried objects can be detected.
- Microwaves and millimeter waves propagate in dust and smoke with low attenuation which enables large propagation distances (up to few kilometers).
- Electromagnetic radiation at typical power-densities is harmless to humans [6], [7].
- They have a low sensitivity with respect to the surface state of the object being investigated.
- Radar modules can be manufactured on a low-cost basis (compare automotive industry).

In this paper, the focus is on the first operational mode where mechanical oscillations are measured behind a barrier material from remote distance. The novelty here is given by an experimental case study in which the sensing performance between a low-cost radar sensor at 24 GHz is compared with a laboratory system at 94.3 GHz.

2 IMPULSE RESPONSE MEASUREMENT

Figure 1 shows an image of the measurement setup in which a laboratory W-band transceiver [8] working at 94.3 GHz and a low-cost 24 GHz sensor are placed on opposite sides of an aluminum beam structure. The goal is to measure the dynamic properties of the beam structure at the same location after impulse excitation. The measurement challenge here is given by the fact that a polystyrene foam is placed in the wave propagation path between the radar sensor and the aluminum plate. Such a non-contact measurement would not be possible with conventional Laser-Doppler-Vibrometer systems.

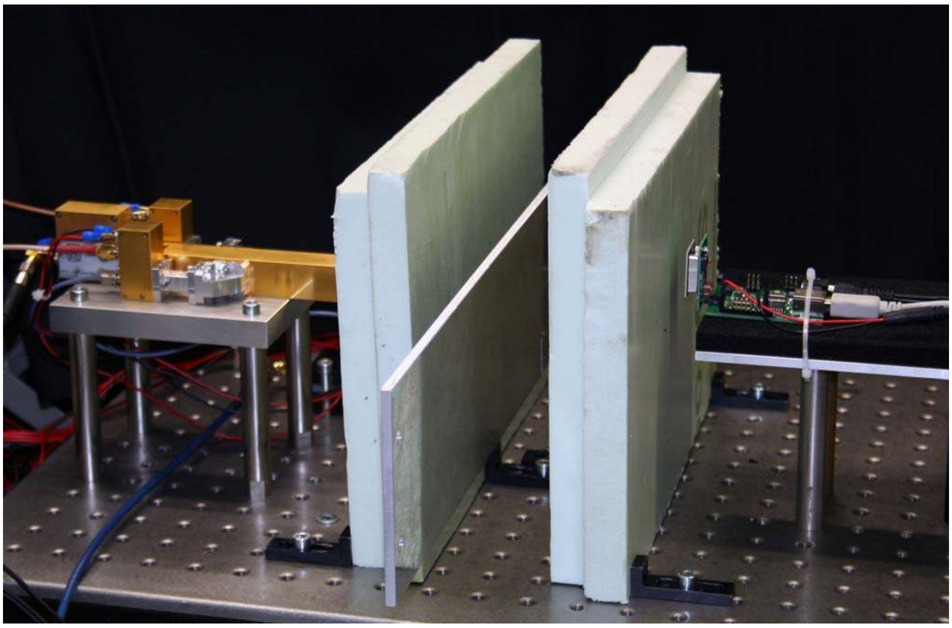

Figure 1: Experimental vibration measurements setup of an aluminum beam behind a barrier material. The laboratory 94.3 GHz system is presented on the left and the low-cost 24 GHz radar sensor on the right side.

Synchronous AD-conversion of the intermediate frequency (IF) signals have been performed with Handyscope instruments HS4 from TiePie Engineering which provides a maximum sampling frequency of 10 MSPS.

The top part of Figure 2 shows the time-domain response of the two radar transceivers. It can be observed that both signals have the identical onset time which represents the time of the impact event. Secondly, the frequency spectra are in good agreement over a relatively broad frequency range and can be observed over a long period of time after the impact. The fundamental vibrational modes can be detected very well and higher order modes are sensed well above the noise background.

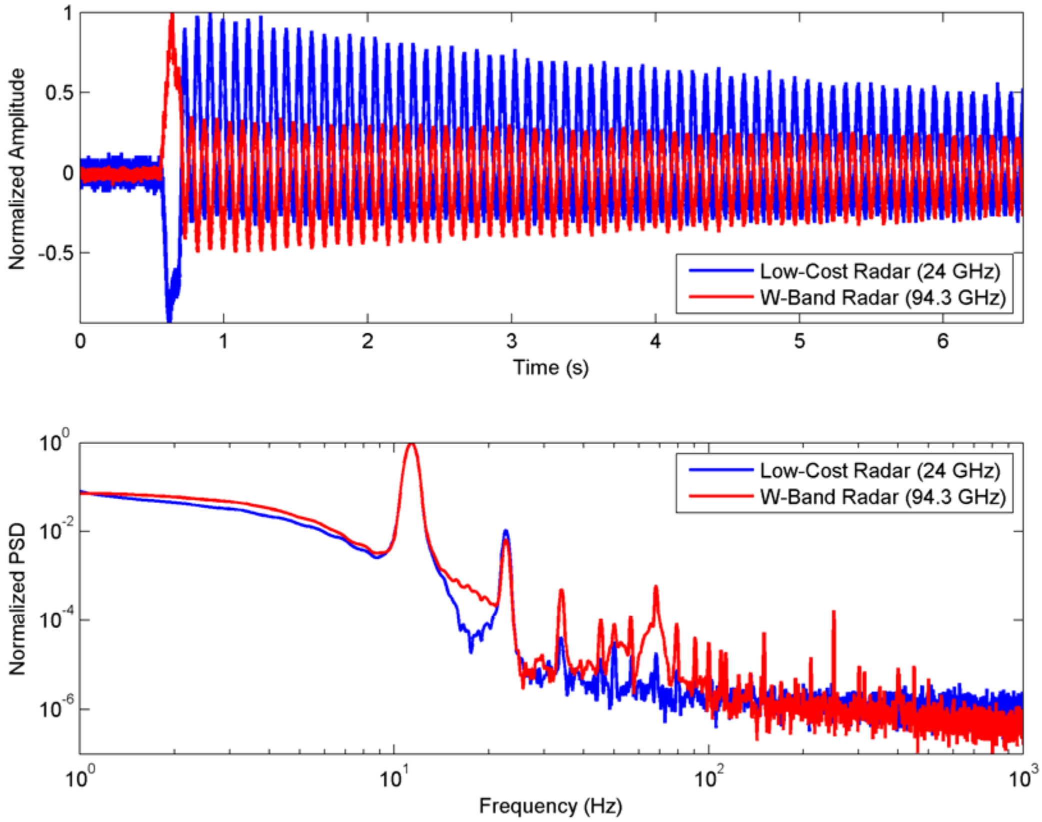

Figure 2: (top) Impulse response in time domain for both transceiver systems; (bottom) Frequency domain representation by means of the normalized power spectral density (PSD). A good agreement was found between the fundamental vibration modes for both frequency bands.

3 DAMAGE DETECTION IN AN AULUMINUM SAMPLE

For SHM-purposes it is important that the sensor is sensitive enough to discern the pristine from the damaged state of the structure. This is demonstrated exemplarily for the low-cost 24 GHz sensor in Figure 3. The undamaged structure can be distinguished from the damaged structure by means of a change in the frequency response. The crack length in this example is 12 mm and 24 mm, respectively. Figure 3 further indicates that also the amplitudes of the higher order vibration modes change with the crack and can be additionally considered for crack detection.

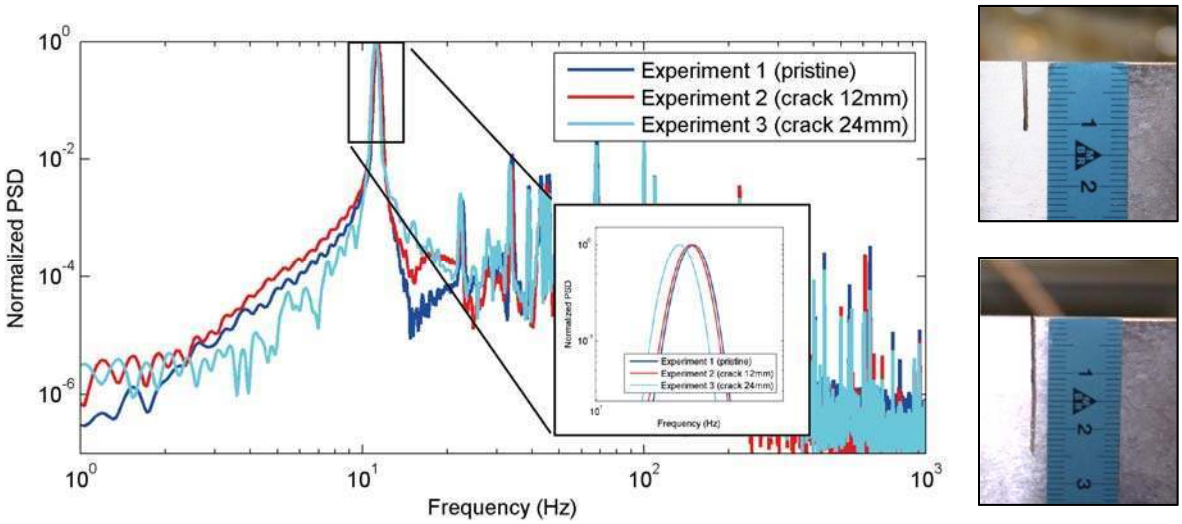

Figure 3: (left) Normalized power spectral density for the pristine and damaged aluminum beam. The crack has a length of 12mm and 24mm, respectively; (right) images of the two considered crack sizes.

4 HARMONIC VIBRATION MEASUREMENTS USING AN UNCONTROLLED SHAKER SYSTEM

A frequency generator drives a shaker system for continuous mechanical excitation experiments as shown in Figure 4. An aluminum plate is mounted symmetrically on top of an uncontrolled shaker system. This enables simultaneous measurements of the same structure by means of both transceiver systems at 24 GHz and 94.3 GHz, respectively. We have investigated vibration frequencies up to 100 Hz and observed that the shaker system is affected by frequency-dependent amplitude variations due to its own dynamic behavior (no dedicated control system was used). In the proposed setup we have arranged the radar sensors in such a way that an orthogonal measurement geometry was ensured. The IF-signals are sampled again with the Handyscope HS4 device mentioned before.

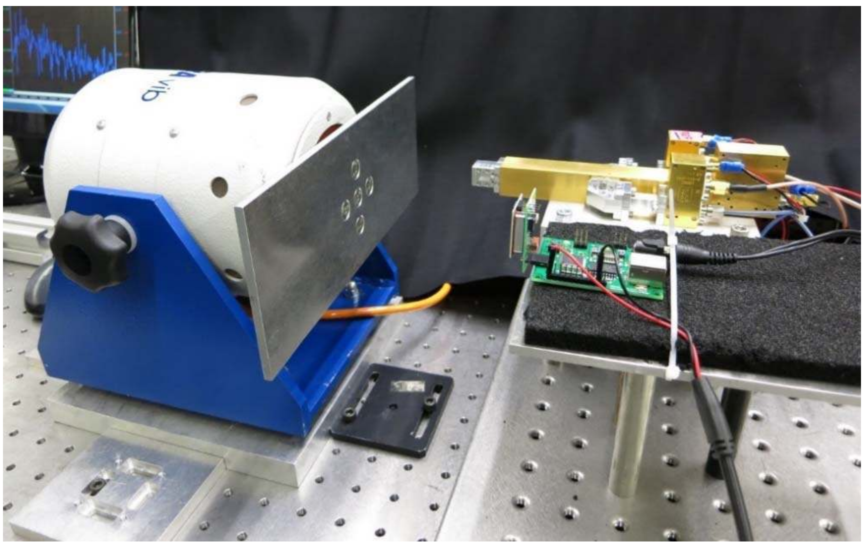

Figure 4: Harmonic vibration measurements using a shaker system and the two transceiver systems.

Figure 5 illustrates two signals recorded by the W-band sensor for small mechanical vibration amplitudes, which corresponds to an amplitude of the frequency generator of 0.04 V and large oscillations with a corresponding amplitude of 1V (the actual displacement amplitude was not available). It can be observed that a different signal to noise ratio can be observed in both cases.

In addition, Figure 6 compares the frequency spectra for harmonic measurements with vibration amplitudes from 1 – 100 Hz. Both radar sensors are able to detect the correct frequency which is an interesting and important finding for SHM applications. Higher harmonics can be observed in both cases. The 94.3 GHz laboratory system outperforms the low-cost sensor system which shows some artifacts, most probably due to antenna sidelobes.

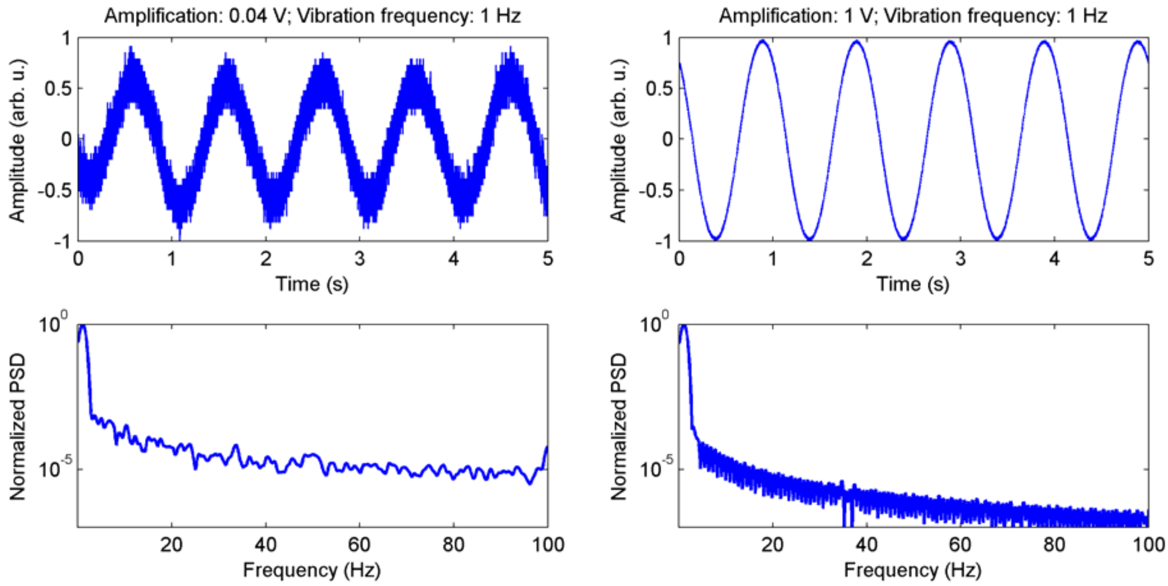

Figure 5: (left) Doppler radar signals for 94.3GHz transceiver at small vibration amplitudes (amplitude of frequency generator: 0.04V) and large vibration amplitudes (amplitude of frequency generator: 1V).

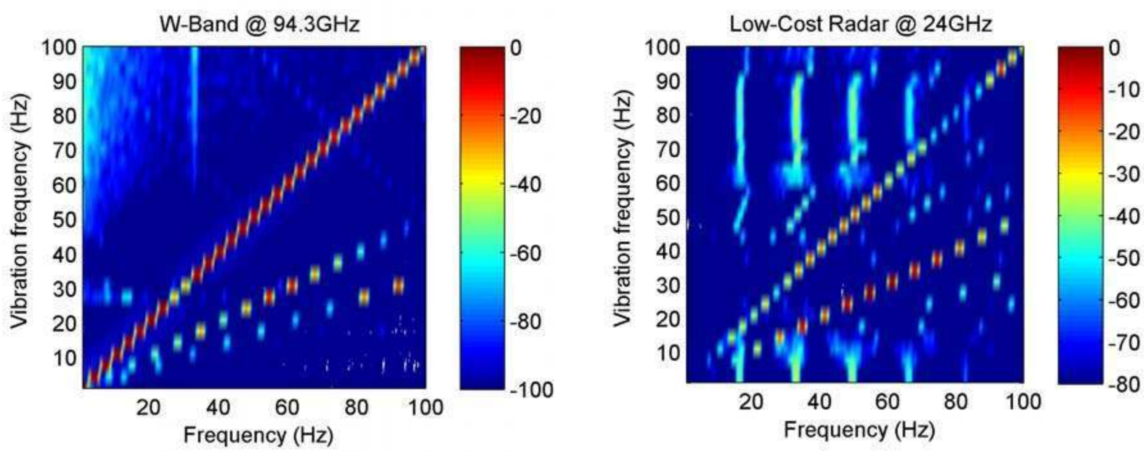

Figure 6: Frequency spectra at vibration frequencies of the shaker system from 1-100 Hz; (left) 94.3 GHz transceiver (right) 24 GHz transceiver. For each vibration frequency also higher harmonics can be seen.

5 CONCLUSIONS

This paper investigated two CW-Doppler radar sensors for mechanical vibration sensing for structural health monitoring applications. It was demonstrated that the laboratory transceiver working at 94.3 GHz and the low-cost 24 GHz system are both able to measure mechanical oscillations behind barrier materials, i.e. a polystyrene foam. Moreover, their capability to identify a crack was shown along with harmonic measurements of a shaker system. This finding may lead to novel applications for radar-based structural health monitoring systems in which the radar sensor can be hidden, e.g. behind a wall or embedded in a radome.

ACKNOWLEDGEMENT

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