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Portable Radar-Based Measurement System for Vibration Analysis of Large Infrastructures

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Summary: We report on the development and validation of a portable and cost-effective radar-based vibration measurement system. Vibration analysis is a powerful tool for structural health monitoring of critical infrastructure subjected to stresses, like environmental factors, loads, and wear over time. Using non-contact sensors avoids sensor installation and enables cost and time-efficient vibration measurements. We present a portable sensor concept based on FMCW radar technology. The system was successfully validated on a high-precision calibration system.

Keywords: Vibration, Infrastructure, Radar, FMCW, Condition Monitoring, SHM, Signal Processing

Introduction

Bridges, tunnels, energy facilities, or public buildings, are key components in the critical infrastructure. However, they are prone to damage and degradation from heavy loads and traffic. Structural health monitoring (SHM) technologies such as vibration analysis are essential to prevent failures and extend their lifespan. However, detecting small changes in vibration frequencies over time of large structures is still technically challenging. Our goal is the development of an accurate, highly portable radar-based measurement system [1]. Radar allows for non-contact measurements, is robust against harsh environmental conditions and captures multiple points simultaneously [2], supporting modal analysis.

Sensor System Hardware Setup

The setup includes a Frequency Modulated Continuous Wave (FMCW) radar, IWR6843ISK, combined with an FPGA, DCA1000EVM, from Texas Instruments (TI). The raw data from the sensor is acquired by the DCA1000EVM via the Low-Voltage Differential Signaling (LVDS) interface, then serialized and streamed via the Ethernet interface as User Datagram Protocol (UDP) packets. Since this setup usually requires TI's proprietary software components, we have developed a custom Python-based library for real-time data processing.

Data Processing Algorithm

The UDP packets obtained from the FPGA are parsed and the obtained IQ samples are processed. A high-level overview of the processing chain is given in Figure 1. A Range-FFT is performed on the IQ samples to determine the distance to the vibrating object under observation.

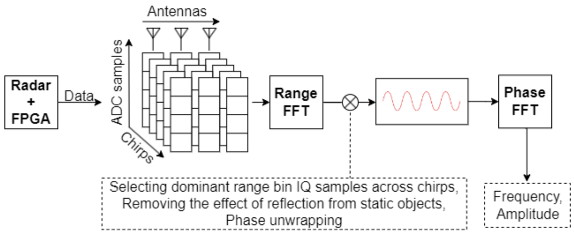

Figure 1: High-level flow of data processing chain

Once the range information is obtained, the dominant range bin is selected, and variations in the phase in that range bin are analyzed. The reflections from static objects are unfavorable as it introduces noise in the phases resulting in inaccurate low amplitude measurements. To remove this effect, data from multiple antennas are used to calculate the static vector and remove it [3]. To remove the phase discontinuities, unwrapping is performed. From the phase change, the displacement is calculated using

$$\Delta d \ = \left(\frac{c}{f}\right) * \left(\frac{\Delta\varphi}{4\pi}\right) * 10^3$$

where Δd is displacement in mm, c the speed of light in m/s, f the carrier frequency in Hz, and $\Delta\varphi$ the phase change in Rad. Various data processing steps, including scaling and windowing, are applied to refine the signal.

Validation of the Sensor System

As large structures have low fundamental frequencies [4,5], the sensor needs high resolution at those low frequencies. This can be achieved with longer measurement duration, which unfortunately contradicts portability and ease-of-use. Figure 2 shows the high-precision calibration system used to qualify the sensor accuracy at low frequencies and high amplitudes.

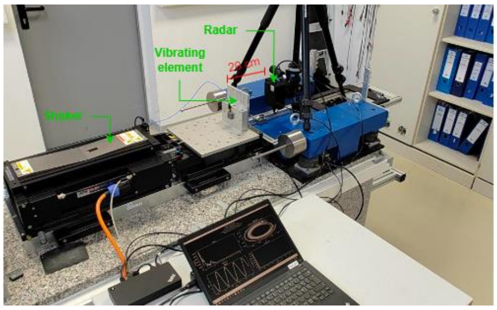

Figure 2: Long stroke vibration exciter APS 129 used for the sensor characterization

For various frequency-displacement combination within this regime, thirty data points for each setting are collected. Each data point is calculated from one second of radar data. The reference value and the measurement median value is shown in Figure 3 in red and black, respectively. The error is not visible within the scale of the plot.

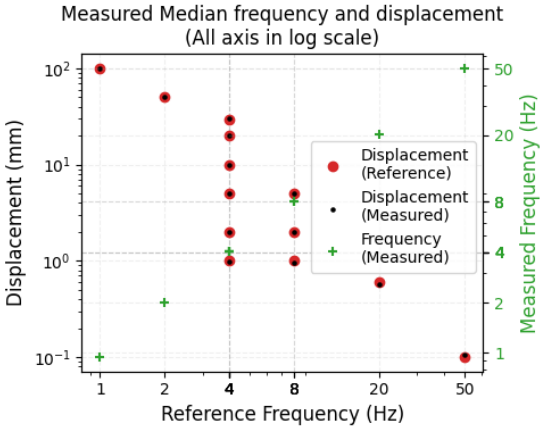

Figure 3: Measured frequency and amplitude

To quantify this, the median absolute percentage error is calculated for all the samples, see Figure 4 and Table 1.

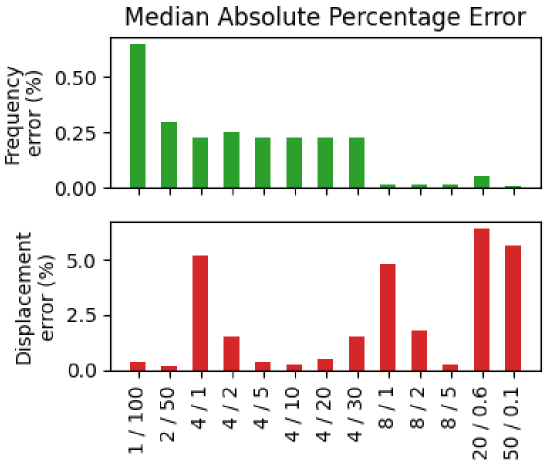

Figure 4: Median absolute percentage error; x-axis labelling: Frequency [Hz] / Displacement [mm]

Analyzing the displacement error across samples shows that the error decreases as the magnitude of displacement increases. This trend is particularly evident in the 4 Hz and 8 Hz samples. For the measured frequencies, the error decreases with increasing frequency.

Table 1: Median absolute percentage error across different frequency displacement combinations

		Displacement in mm									
		0.1	0.6	1	2	5	10	20	30	50	100
Frequency in Hz	1										0.646 0.388
	2									0.296 0.183	
	4			0.225 5.225	0.248 1.541	0.225 0.366	0.225 0.235	0.225 0.518	0.225 1.518		
	8			0.01 4.779	0.01 1.793	0.01 0.238					
	20		0.053 6.442								
	50	0.01 5.655						Frequency error in % Displacement error in %			

Two main factors contribute to this trend: the limited duration of each measurement instance and the error metric used, which disproportionately penalizes small frequencies.

Summary and Future Directions

We have presented a FMCW-based vibration measurement system intended for SHM of large infrastructures. Radar offers many advantages over tactile sensors, such as robustness and portability. We have successfully validated the sensor on a commercial calibration system. While the error is generally very low, it will remain challenging to achieve a high measurement resolution at low frequencies under real-world conditions.

The radar cross section (RCS), material reflectivity, and surrounding noise are the main factors affecting the signal quality of a target. Future work will include advanced focusing techniques such as digital and lens-based beamforming, beam nulling, and algorithm improvements.

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