Radar Vibrometry: Investigating the Potential of RF microwaves to measure vibrations

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Abstract: Expanding radar applications in the area of measuring vibration movements could improve the effectiveness of modern defence systems. The purpose of the vibration measurement is to enrich the information of a targets signature, thus improving the process of target identification and classification. The basic mathematical models of a single receiver radar and a radar that operates as an interferometer are presented. Based on the first model, a simulation is conducted in order to assess the ability of the radar to act as a vibrometer in the presence of Additive White Gaussian Noise (AWGN) and phase noise.

1. Introduction.

The efficiency of modern defence systems depends significantly on target identification and classification. The performance of such systems is mainly evaluated by their effectiveness under any ambient conditions and their ability to distinguish between different types of targets. High resolution radar imagery, IR camera and 3D laser cameras have been used as methods for target identification but with limited effectiveness [1]. Distinguishing between different types of targets requires the extraction of such features that are unique for each target, thus formulating a signature. By measuring vibrations of targets' surfaces and analysing the vibration spectrum we are able to define a vibration signature that can be regarded unique for each target [2].

Radar systems are mainly used for detecting objects and determining their location and speed. The acquisition of information about the target relies on the fact that the radar transmitted signal will have its properties changed when it is reflected by the target. However, the received signal does not contain information related only to the position and speed of an object. Mechanical vibrations of targets' surfaces induce modulations on the backscattered electromagnetic signal that contribute to the target signature. The phase of the reflected signal is affected by the variation in range introduced by the vibrations. This phase modulation if seen in the frequency domain, introduces the micro-Doppler effect which can be considered as an additional Doppler variation to the translation Doppler shift [2]. In whatever form it is expressed, the vibration signature provides additional information about the target. When combined with other methods it may improve the effectiveness of the target classification process.

Recent research on vibrometry, the process of conducting vibration measurements, is mainly focused on the use of lasers. The small wavelength, the laser radars use, enables them to measure even micron movements very accurately. The relationship between the wavelength and the vibration amplitude sensitivity will be shown in a later part of the paper. Moreover, laser radars' (LADAR) narrow field of view makes them impervious against interference. However, the fact that the performance of these systems is highly affected by the weather conditions and speckle [3], limits their effectiveness. On the other hand, the capability of modern RF radars to operate under any weather conditions and their extensive use as detection systems makes them candidates for performing vibrometry measurements.

With this study we make a primary investigation of the capabilities of RF radar systems to measure vibrations. We examine the basic concepts of radar vibrometry and we conduct computer simulations in order to evaluate the performance of a radar that measures vibrations of simple targets in the presence of noise.

2. Mathematical Background and Analysis.

We examine the mathematics of vibrometry by analysing the modulation that is induced on the returned radar signal. In order to simplify the analysis we consider movements only on the 2-dimensional (2D) space. The analysis can be expanded to the 3-dimensional (3D) space without any significant modification. Moreover, we will consider the vibrating target to be a single point scatterer. More complicated targets can be represented as a set of point scatterers [2]. We consider two different cases for receiving the signal: the use of a single receiver and the use of two receivers that form an interferometer.

Single Receiver. As shown in figure 1, the radar is stationary and located at the origin of the X-Y plane. We consider the target vibrating sinusoidally with an amplitude A and frequency f_v at an angle of θ in respect to the line-of-sight (LOS). The reflected signal is only sensitive the vibration component that lies on the LOS. So the vibration movement perceived by the radar will be described by the equation $V(t) = A_v \cos(2\pi f_v t)$ (1) where

$A_v = A\cos\theta$ (2). We also consider that the radar is operating at a frequency f_c so that the transmitted signal is described as $s_t(t) = A_S \cos(2\pi f_c t)$ (3), where A_s is the voltage amplitude of the transmitted waveform. A change in range of ΔR will induce on the reflected signal a phase shift $\Delta\phi = \dfrac{4\pi\Delta R}{\lambda}$ (4) where λ is the wavelength corresponding to frequency f_c. As the range of candidate target types varies from human movement to armoured vehicles the expected vibration frequencies are in the range of a few Hz to some kHz and the vibration amplitudes vary from centimetres to microns. Table 1 shows the phase shift induced by different range changes which in our case correspond to different vibration amplitudes. A vibration amplitude of 1 micron results in a phase shift of only 0.024° that is almost undetectable. On the other hand, the phase shift in the case of lasers is much bigger because of the small wavelength it is used. However, for bigger vibration amplitudes we could face the problem of phase wrapping because the phase shift could exceed the limits of ±180°.

The reflected signal received by the radar will be described as $s_r(t) = A_r \cos[2\pi f_c t + \dfrac{4\pi R_0}{\lambda} + \dfrac{4\pi\Delta R}{\lambda}\cos(2\pi f_v t)]$ (5), where R_0 is the targets initial distance from the radar. It is the case of a phase modulated wave with modulation index $\beta = \dfrac{4\pi\Delta R}{\lambda}$ (6). Generally we face a narrowband modulation as for the most of the expected vibration amplitude values we have β<1. However, for amplitudes in the order of cm the modulation index is near to 1 so that the modulation becomes wideband. Extraction of the information in the received signal will be performed by phase demodulation techniques.

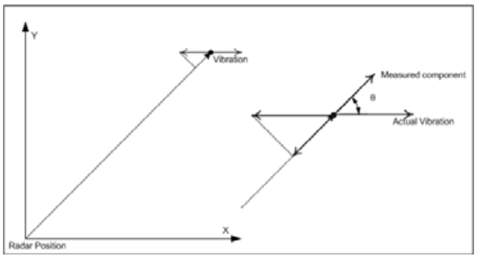

Figure 1: Geometry of target and single receiver

Vibration Amplitude	Maximum Phase Shift (degrees)
1μm	0.024
1 mm	24
1 cm	240

Table 1: Sensitivity of a 10 GHz radar to different vibration amplitudes

Interferometer. Single receiver lacks the ability to detect vibrations with direction perpendicular to the LOS. In order to overcome this problem we use two receivers that form an interferometer as shown in figure 2. In this case the vibration movement is mapped on the change of the phase difference between the two receivers according to the equation $\Phi(t) = \Delta\varphi = \dfrac{2\pi(R_2(t) - R_1(t))}{\lambda}$ (7). As seen in figure 3, the change of the phase difference, namely the sensitivity of the interferometer for a given baseline, maximizes when the vibration movement is parallel to the baseline and perpendicular to the LOS. However, the interferometer is not very sensitive in detecting micron movements. As can be seen in figure 4, even for a baseline over distance ratio equal to 0.1, the phase change induced by 1 mm vibration amplitude is nearly equal to 1 degree.

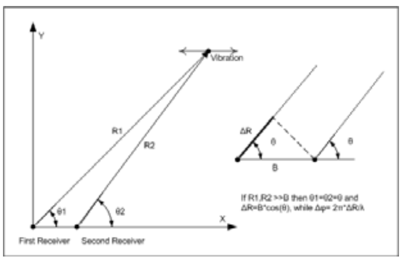

Figure 2: Geometry of target and interferometer

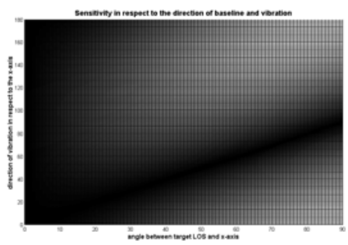

Figure 3: Sensitivity in respect to the look angle and the direction of the vibration. Darker areas denote decreased sensitivity.

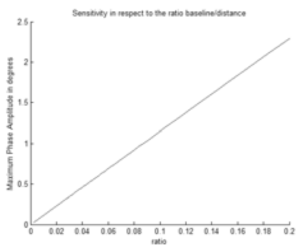

Figure 4: Interferometry sensitivity in respect to the ratio baseline/range when A_v=1 mm.

3. Simulation.

A primary evaluation of the performance of a single receiver radar as a vibrometer is conducted with the use of a simulation study in MATLAB. We analyse the complex envelope of the received signal described by equation 5. The complex envelope of $\mathbf{s_r(t)}$ is: $s_c(t) = A_r e^{j\frac{4\pi(R_0 + A_v \cos(2\pi f_c t))}{\lambda}}$ (8). The tool that we are going to use for the analysis is the Fast Fourier Transform (FFT), so that we acquire information about the vibration from the spectrum of the received signal.

In figure 5 we see the spectrum that corresponds to a signal modulated by a 10μm movement with vibration frequency 10 Hz. The radar operates at 10 GHz. Therefore, according to equation (6), the modulation index is equal to **β= 0.004<1**. That is the reason why only a single spectral line is observed at 10 Hz. However, as seen in figure 6, when the vibration amplitude becomes 1 mm, the modulation index becomes **β=0.4,** a value close to 1. In that case the modulation tends to become wideband and more spectral lines appear.

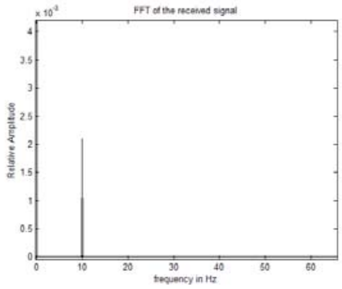

Figure 5: Spectrum of the $s_c(t)$ when A_v=10μm, f_v=10 Hz and f_c=10 GHz

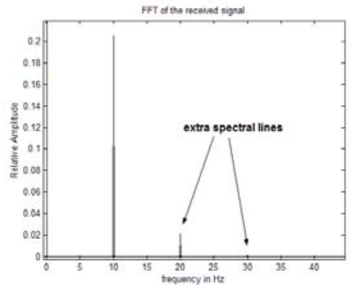

Figure 6: Spectrum of $s_c(t)$ when A_v=1mm, f_v=10 Hz and f_c=10 GHz

Complex Gaussian Noise. The complex envelope of the received signal in the presence of noise will be given by: $s_c(t) = A_r e^{j\frac{4\pi(R_0 + A_v \cos(2\pi f_c t))}{\lambda}} + n(t)$ (9), where $n(t)=n_r(t)+jn_i(t)$ (10) is a complex valued white, zero mean Gaussian stochastic process [4]. We also consider the real and imaginary components to be uncorrelated with variance σ^2. In that case the Signal to Noise (SNR) ratio will be $SNR = \frac{A_r^2}{2\sigma^2}$ (11). For the study of the complex noise we consider a vibration movement with amplitude 100μm and frequency 10 Hz. In figures 7 and 8 we can see that the complex noise level becomes comparable to the part of the signal produced by the vibration when SNR is lower than 0 dB.

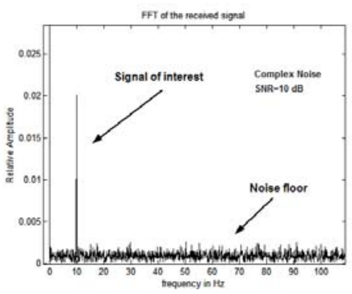

Figure 7: Spectrum of $s_c(t)$ when A_v=100μm and SNR=10 dB

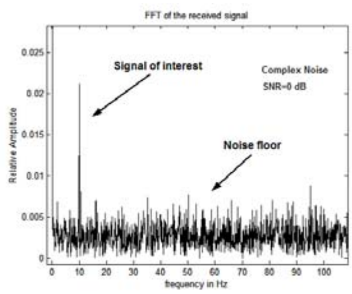

Figure 8: Spectrum of $s_c(t)$ when A_v=100μm and SNR=0 dB

Phase Noise. We consider the case when the received signal is affected by phase noise. The complex envelope will be given by: $s_c(t) = A_r e^{j\left[\frac{4\pi(R_0 + A_v \cos(2\pi f_c t))}{\lambda} + n_P(t)\right]}$ (10) where $n_P(t)$ is a random variable with uniform distribution in the area [$-n_{p\_max}$, n_{p_max}]. The value of n_{p_max}, which must be lower than π rad, defines the amount of phase noise added to the received signal. In the figures 9 and 10 we consider a vibration amplitude of 10μm that induces 0.25 degrees phase shift to the transmitted signal. Phase noise starts distorting the signal only when the maximum phase noise value is greater than 10°.

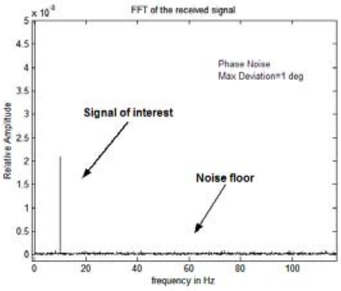

Figure 9: Spectrum of $s_c(t)$ when A_v=10μm and n_{p_max} =1°.

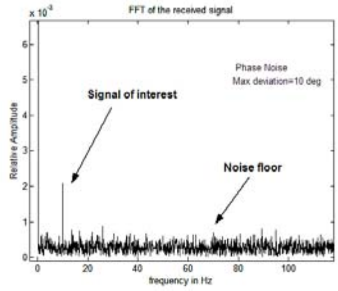

Figure 10: Spectrum of $s_c(t)$ when A_v=10μm and n_{p_max} =10°.

4. Discussion and Conclusions

The vibration of a target induces a phase modulation on the radar reflected signal. The form of the modulation depends on the characteristics of the vibration movement such as the frequency, amplitude and direction.

From the mathematical analysis on the vibrometry concept it can be seen that when a single receiver is used as the detector, only the vibration component on the radar's line of sight is measured. The modulation depth varies in accordance with the amplitude of the vibration. For amplitudes of the order of microns the phase shift induced on a RF-signal is only a fraction of a degree. Therefore during the demodulation process a high degree of coherency is demanded. On the other hand, vibration amplitudes of the order of cm cause overmodulation which leads to phase wrapping.

In the case of interferometry, we exploit its advantage to measure vibrations perpendicular to the radars line of sight. However, for small baseline/range ratios the induced phase shift is equal to just a small proportion of a degree and therefore it is difficult to be detected. Interferometry becomes useful only when the vibration amplitude is of the order of cm and the radar-target range is comparable to the length of the radar baseline.

The effects of complex noise on the received signal depend on the modulation depth. The simulation has shown that even for vibration amplitudes smaller than 1 mm the spectral lines observed are of significant power. Therefore the performance of the detector is limited only under poor conditions (SNR <0 dB). Taking into account that most radar systems operate in an environment with SNR bigger than 13 dB we can presume that even vibrations with amplitudes smaller than 1 mm could be detected.

The phase noise becomes noticeable only in the case when the vibrations to be detected are of small amplitude, thus introduce small phase shifts. However, even when the phase shift is just a quarter of a degree and the maximum phase deviation introduced by the phase noise is 10 degrees we can see from the signal spectrum that the spectral line corresponding to the signal of interest is at a much higher level than the noise floor.

Future work will be focused on the analysis of more complex targets and complex vibrations. The analysis will move from the simple point scatterer to surfaces. Moreover, when the target vibrates with more than one frequency, it is expected that in the spectrum of the received signal will appear intermodulation products. As far as the tools for the signal analysis are concerned, it appears that time-frequency analysis techniques provide rich information about the vibration movements and as such they could be considered as a valuable tool in retrieving an objects vibration signature.

References

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