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A third-order harmonic radar design for mm-Wave frequencies

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ABSTRACT

The nonlinear properties of electronic devices, such as diodes and transistors, can generate nonlinear responses such as harmonic and intermodulation for clutter rejection purposes. The naturally occurring clutter objects are generally linear, or they possess very small nonlinearity. They can be distinguished from man-made targets containing the above-mentioned nonlinear devices by exploiting nonlinear responses. In this paper, this nonlinear property was utilized for generating a 3rd-order harmonic response for clutter rejection purposes. Existing nonlinear radars generally exploit 2nd-order harmonic responses for clutter rejection purposes owing to their high power levels among the harmonic responses. However, due to their proximity to the fundamental tone, these radars require bulky and expensive filters and diplexers with steep roll-off for maintaining the linearity of the transmitter and receiver section of the radar. As the 3rd-order harmonic response and the fundamental tone are widely separated in the frequency spectrum compared to the 2nd order harmonic response, better isolation between the fundamental and harmonic response can be achieved. This results in relaxed requirements for filters and diplexers for these 3rd order based harmonic radars. Apart from that, the receiver and tag size would be reduced since size and frequency are inversely proportional. In this paper, the 3rd-order harmonic radar and a passive tag were designed and operated in millimeter-wave frequency bands, i.e., 24/72 GHz. Experimental validations were performed to prove their clutter rejection ability.

Keywords: harmonic, third-order, mm-Wave, Doppler, clutter rejection.

1. INTRODUCTION

Continuous-wave (CW) radars were first utilized in the 1930s for measuring the motion of the target. Since then, radars have undergone significant transformations. Initially, radars were limited to military use; however, nowadays, radars have penetrated deep into our daily life ranging from automotive radars for collision prevention, weather observation and forecasting, and the health care sector.

These CW radars can measure the Doppler frequency with high accuracy[1]. However, they cannot differentiate clutter from the target without prior or post adjustment. They either require specialized hardware setup[2] for suppressing a limited clutter or a software-based approach such as curve fitting[3], wavelet-based processing[4], cyclostationary[5] algorithm. These software-based approaches can make the system not operate in real-time.

The CW radars utilize active backscatterer based tags for differentiating the clutter from the target of interest. In these radars, an active tag is placed on the target. This active tag contains an antenna, a mixer, and a signal generator. The transmitted frequency f from the radar is captured by the tag, the signal generator, and the mixer modulate this frequency and backscatter $f \pm f_m$ towards the radar. The target is identified bases on the f_m frequency, since natural clutter will only reflect f. Since these tags are active, the life cycle is dependent on the battery life.

For solving the issue with the lifecycle of the tag, generally, nonlinear-based radars are used. These radars do not need pre- or post-calibration or specialized hardware setup. Instead, they exploit the electronic devices' nonlinear response

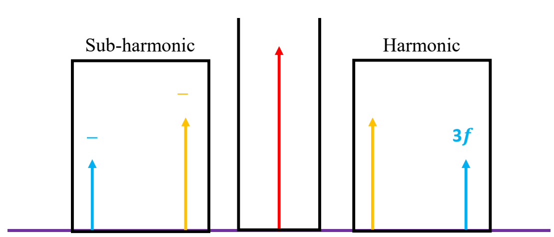

Figure 1. Nonlinear responses when one fundamental tone passes through a nonlinear device.

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to differentiate the clutter from the target. Most of the naturally occurring clutter sources are linear in behavior; hence they can be differentiated from the nonlinear man-made components.

In a nonlinear radar, fundamental tone(s) are sent out into the environment, and the natural clutter reflects the fundamental tone(s). In contrast, the tag that contains a nonlinear device backscatters the fundamental response and also the nonlinear response back towards the target. Figure 1 shows the nonlinear responses generated when a fundamental tone is passed through a nonlinear device. Based on this nonlinear response, the target can be differentiated from the clutter. Most of the reported nonlinear radars work by detecting the 2nd order harmonic response[6,7] or the 3rd order intermodulation response[8,9]. In these radars, the nonlinear responses are close to the fundamental tones, hence requiring expensive diplexer and filters for removing the fundamental responses from the received signal and nonlinear responses from the transmitted signal.

In the previous works on harmonic radars[10-12], the 2nd order harmonics have been extensively utilized to design the harmonic-based nonlinear radar. The 2nd order harmonics being close to the fundamental, these nonlinear radars require expensive and bulky diplexers, filters, and other frequency cancellation schemes for removing harmonics from the transmitter path and fundamental in the receiver path.

In intermodulation radars[13], the nonlinear response and the fundamental response lie in the same band; hence the path loss of the nonlinear and fundamental tones is almost identical. Since all the frequencies lie in the same band, rejecting fundamental in the receiver and intermodulation in the transmitter requires filters or diplexers with very steep roll-off to reject the unwanted frequency. This makes it difficult to operate at high-frequency bands since designing filters or diplexers to attenuate and pass the same band frequencies becomes difficult as one goes higher in the frequency band.

The subharmonic response[14] was also utilized for clutter suppression. In these radars, the path loss of the subharmonic response is lower compared to fundamental at the cost of a large receiver size. However, these radars require active tags for their operations.

The above-discussed nonlinear radars are either large and bulky, making them not portable, or they require active tags, thus limiting the lifetime. Thereby limiting their applications. For easy deployment purposes and to increase the radars' applications, they need to be portable and handheld for clutter rejection with passive tag. Some of these radars' applications are locating humans trapped under natural disasters, in the healthcare industry for monitoring desired patients' activities, authentication purposes, etc. Since the 2nd order harmonics and fundamental tone is close and hence these radars require expensive filters and diplexers to maintain the linearity of the transmitter and receiver. The intermodulation radars also encounter this same issue. Utilizing higher-order intermodulation response would also not solve this issue due to their proximity to the fundamental. For every 1 dB drop in the fundamental tones' power level, the nth order intermodulation response drops by n-dB. Due to the increased dependence of fundamental tone power level to the intermodulation response's power level, this leads the radar to operate up to a limited distance to maintain desired sensitivity. Utilizing higher-order harmonics can be a better option for reducing the radar size. In this work, a new nonlinear radar was designed which operated in higher-order harmonics, i.e., 3rd order harmonics; in this radar, the fundamental and 3rd order harmonic response can be attenuated by the RF components in the receiver and transmitter chain itself since they are so far apart in the frequency spectrum, which would ultimately help in reducing the size the make the system portable. The S-parameter of an RF amplifier with a gain of 40-dB was measured on VNA. The S21 measurements were 40 dB at the fundamental frequency, which dropped to 2.3 dB at the 2nd order frequency location and -20 dB at the 3rd order harmonics location. Please note that the operating frequency of the amplifier was within the fundamental frequency region only. Theoretically, the amplifier should also generate 3rd order and higher harmonics; however, the packages, matching circuit, and other factors lead to the amplifier not operate at higher harmonics. This would lead to the radar not using additional filters or diplexers for unwanted frequency cancellations making the system small, portable and low cost. Higher harmonics could also be utilized; however, their low power level could affect the radar's sensitivity.

In this paper, a harmonic radar is designed, which utilizes 3rd order harmonic to distinguish the target from clutter. A radar was designed to transmit frequency at 24 GHz and receive 72 GHz frequency from the tag. Since the fundamental and harmonic response was widely separated in the frequency band, hence the RF components in the transmitter and receiver attenuated the unwanted frequency without the use of additional filter or diplexer compared to the intermodulation based and 2nd order harmonic based nonlinear radar. The tag used for the measurement was passive.

The paper is divided into four sections. In the second section, the theory and design of the radar are discussed, section three deals with measurement and results. A conclusion is drawn in section four.

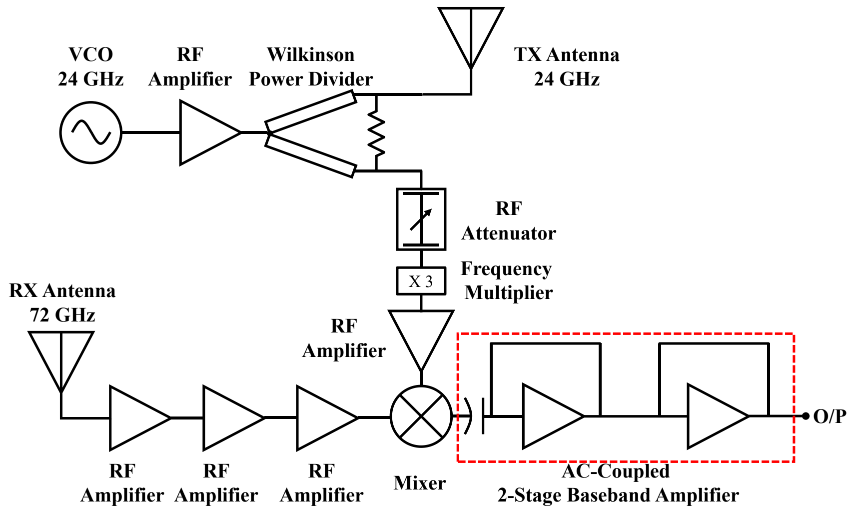

Figure 2. Block diagram of the harmonic radar.

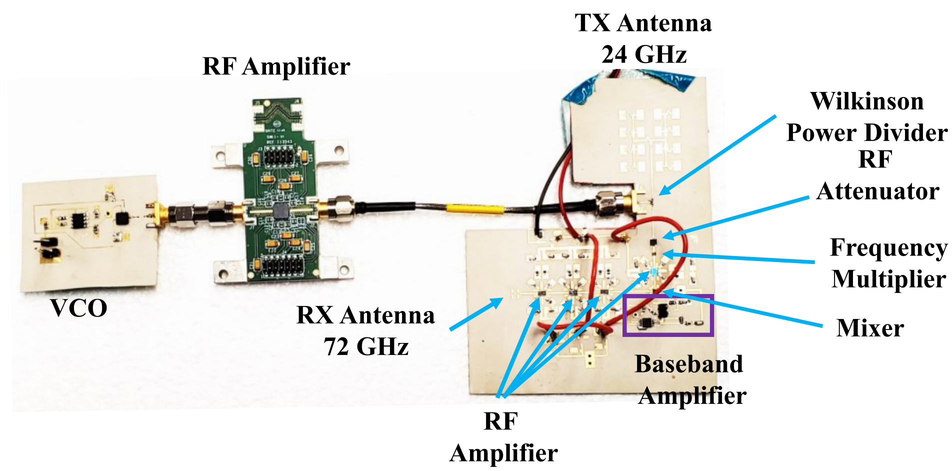

Figure 3. A 24/72 GHz harmonic radar system.

2. THEORY AND DESIGN

2.1 Harmonic response

When a fundamental frequency tone f is allowed to pass through a nonlinear device, the nonlinear device generates additional frequency to tones at nf, where $n > 1$. These additional tones are called harmonic responses, and the order of the harmonic response is determined by n. The nonlinear radar utilizes these harmonic responses to distinguish clutter from the target.

2.2 Theory

The frequency transmitted from the transmitter antenna TX can be written as

$$T(t) = \cos[2\pi f t + \phi(t)] \tag{1}$$

where ϕ is the phase noise of the voltage-controlled oscillator (VCO) and t is the time. The nonlinear tag captures the transmitted frequency, and the tag backscatters fundamental along with 3rd order harmonic response $3f$ towards the

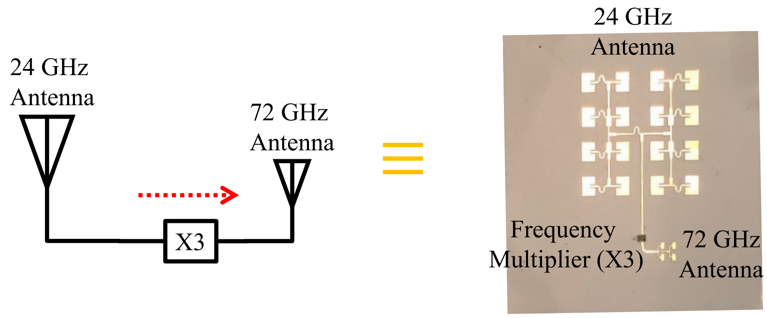

Figure 4. 3rd order harmonic tag at 24/72 GHz frequency band.

radar. Since the receiver rejects the fundamental tone, so in the received signal, frequency f will not be used in the reflected signal. The reflected signal from the tag can be written as

$$R(t) = \cos\left[6\pi f t - \frac{4\pi x_o}{\lambda} - \frac{4\pi x(t)}{\lambda} - \phi\left(t - \frac{2x_0}{c}\right)\right] \tag{2}$$

In (2) λ represents the wavelength corresponding to $3f$, $x(t)$ was the mechanical displacement of the target wearing the tag and x_0 is the nominal distance between the target and radar. The fundamental tones reflected by the clutter cannot pass since the antenna, RF amplifiers work in a $3f$ frequency band.

The transmitted frequency signal passed through a frequency multiplier which multiplies the transmitted frequency by three before it is fed to the LO port of the mixer; hence the LO port signal can be written as

$$L(t) = \cos[6\pi f t + \phi(t)] \tag{3}$$

The mixer down-converts the RF signal with the LO signal, and the output signal is sent towards the AC-coupled baseband amplifier. The baseband response can be written as

$$B = A\cos\left[\frac{4\pi x_o}{\lambda} + \theta_0 + \frac{4\pi x(t)}{\lambda} + \Delta\phi(t)\right] \tag{4}$$

where, θ_0 denoted the phase shift when the signal is backscattered by the tag and propagates along the receiver chain. $\Delta\phi(t)$ is the residual phase-noise and can be ignored since the same VCO is used for RF and LO signal, and a similar frequency multiplier is used in the LO and the tag. A represents the gain of the baseband amplifier.

2.3 Radar design

Figure 2 shows the block diagram of the 24/72 GHz harmonic radar. A 24 GHz VCO was used to generate the transmitting frequency. The VCO output was sent towards the 24 GHz RF amplifier, which amplified the signal and sent it to the Wilkinson power divider. One output of the Wilkinson power divider goes towards the TX antenna, which radiated the 24 GHz frequency. The other path of the Wilkinson power divider goes towards the LO path. Here, the output of the Wilkinson power divider is sent towards the attenuator, which attenuates the power level of the 24 GHz signal to be below the maximum power level that the frequency multiplier can handle. The attenuator's output is fed to the frequency multiplier; here, the 24 GHz signal is converted to 72 GHz. The conversion loss of the multiplier is 19 dB. To operate the mixer, the desired power level is needed for the 72 GHz frequency tone. So the output of the frequency multiplier was sent to the 72 GHz RF amplifier. The amplifiers' output is given to the LO port of the mixer.

The tag captures the transmitted tone, generates the 72 GHz signal from the multiplier, and reflects it towards the radar. The radar allows the 72 GHz signal to pass through the receiving antenna RX and discards the 24 GHz signal reflected from the naturally occurring clutter. The received signal, i.e., 72 GHz signal, is passed through the 72 GHz

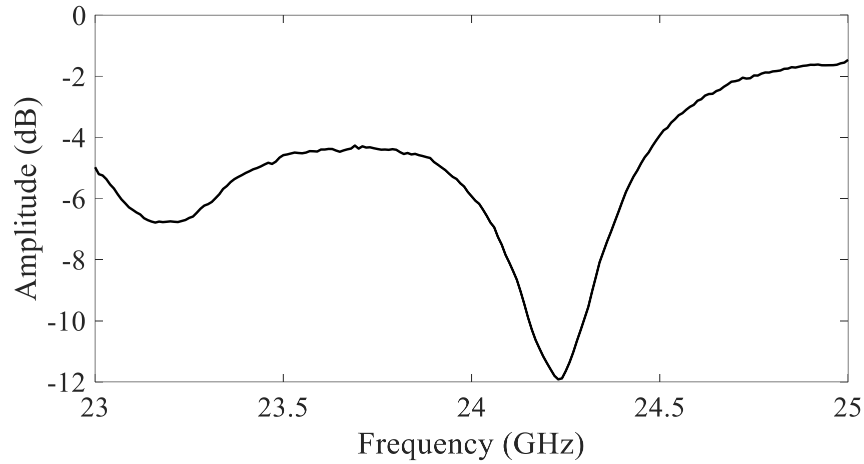

Figure 5. Measured S11 of 24 GHz antenna.

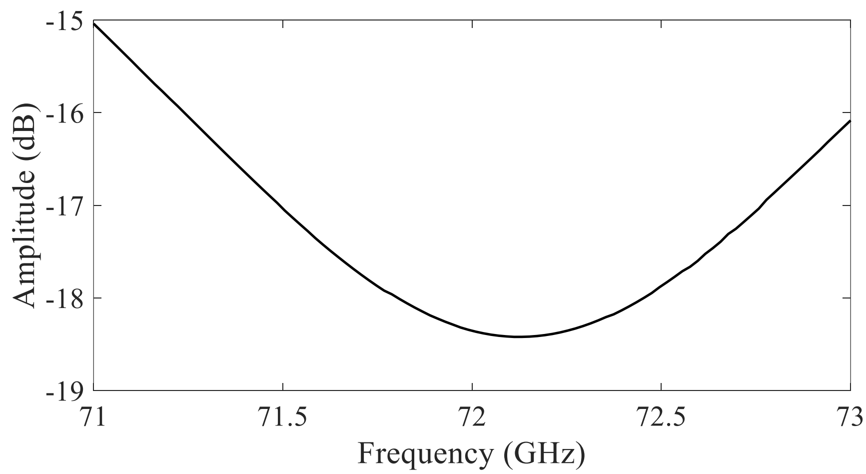

Figure 6. Simulated S11 of 72 GHz antenna.

RF amplifiers, which adds gain to the received signal. This signal is sent towards the RF port of the mixer. At the mixer, the RF port signal is down-converted by the LO port signal, and the output is sent towards the AC coupled baseband amplifier. The baseband amplifier amplifies the baseband response, and it is sent to the data acquisition (DAQ) device for recording on the computer. Figure 3 shows the hardware prototype of the radar.

2.4 Tag design

Similar to most parts of the 3rd-order harmonic radar, the nonlinear tag was also designed on Rogers RO 3006 substrate with 0.254 mm substrate thickness. Figure 4 shows the block diagram and hardware prototype of the passive tag. The Analog Device HMX-XTB110 was used as the frequency multiplier. The tag contains two antennas, one tuned at 24 GHz which acts as the tag's receiving antenna, and the other at 72 GHz acts as the transmitting antenna and the frequency multiplier. The receiving antenna captured the fundamental response and sent it towards the frequency multiplier, where the response corresponding to 3rd harmonics is generated. The generated 3rd order response is sent towards the transmitting antenna for backscattering purposes. Since the tag is passive hence the lifetime of the tag is dependent on wear and tear.

The 24 GHz tone was captured by the 24 GHz antenna and was passed through the frequency multiplier. The frequency multiplier converted the 24 GHz signal to the 72 GHz signal. The 72 GHz signal was sent reflected towards

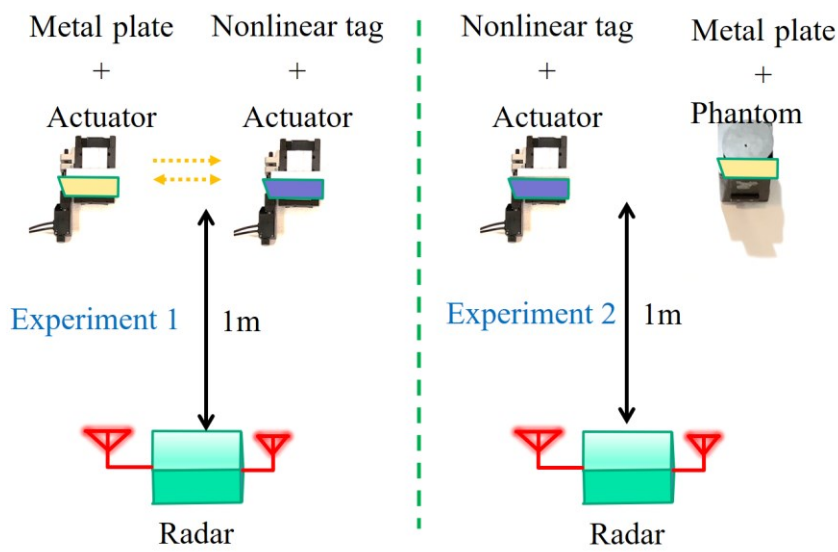

Figure 7. Experiment setup for measuring Doppler motion and clutter rejection.

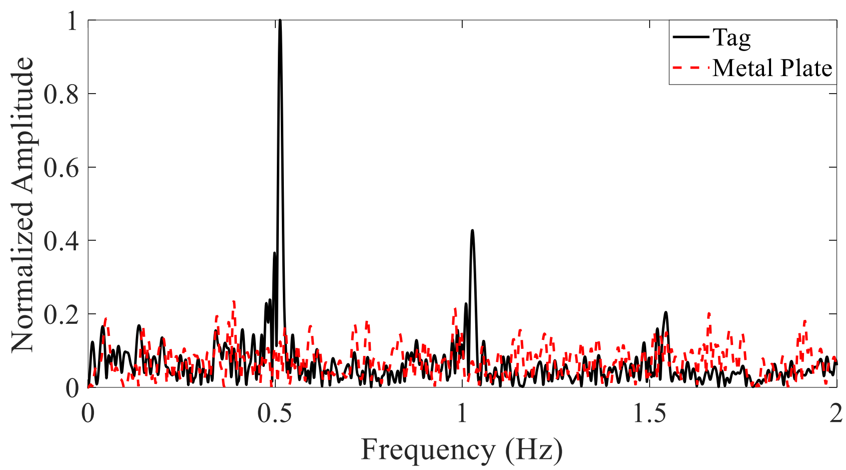

Figure 8. FFT plot for the experiment when tag and metal plate were placed on the actuator sequentially and motion amplitude and frequency were kept equal.

the radar via the 72 GHz antenna of the tag. Figure 5 shows the S11 plot of the 24 GHz antenna measured on the Vector Network Analyzer (VNA), and the simulated result of the 72 GHz antenna is shown in Figure 6.

The radar transmitted a 24 GHz tone with a power level of 30 dBm. The gain of the 24 GHz antenna used in radar and tag was approximately 15 dB. There is at least 30 dB path loss for a distance of 1 m. Hence 0 dBm power is received by the tag. The conversion loss of the frequency multiplier is 19 dB. As a result, the 72 GHz tone is generated with a power level of -19 dBm at the tag. The 72 GHz antennas have a realized gain of 8.3 dB. This results in 53 dB of path loss. So 72 GHz tone with a power level of -72 dBm is received by the radar. The path loss calculations were performed as per the free-space path loss model.

3. MEASUREMENT AND RESULT

Two experiments were performed to validate the clutter rejection ability of the radar. The experiments were performed in a typical lab environment. In this experiment, a metal plate was used as linear clutter, reflecting the fundamental tone which was incident on it. While the target, i.e., the nonlinear tag, would reflect the 3rd order harmonic response

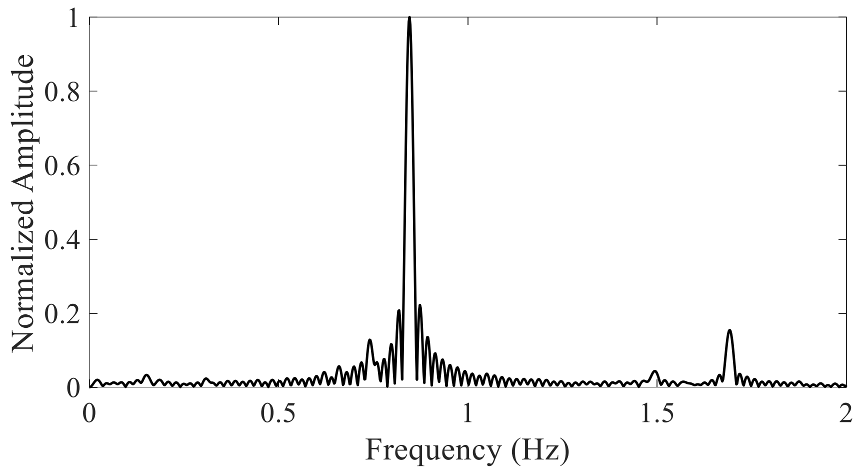

Figure 9. FFT plot for the experiment when tag and metal plate were placed on the actuator and phantom respectively, and motion amplitude of the tag was lower than that of the phantom.

and the fundamental back towards the radar. And based on the 3rd order harmonic response, the clutter would be differentiated from the target. The two experiments performed were : (a) nonlinear tag vs. metal plate and (b) motion of the tag in the presence of large motion from clutter.

3.1 Experiment 1: nonlinear tag vs. metal plate

The experiment was performed to validate the radar's clutter suppression performance. Hence the target's motion, i.e., the tag mounted on the actuator, was differentiated from the clutter motion i.e., metal plate mounted actuator. Here the measurements were performed sequentially. In the first experiment, the metal plate was placed on a linear actuator (Zaber T-NAOSA50), and the motion of the actuator was set at 0.1 mm peak-to-peak with the motion frequency set at 0.5 Hz. The linear actuator is a device that generated linear motion with the user-defined motion amplitude and frequency. The measurement was recorded using NI-USB 6009. After this, the metal plate was replaced with the tag. The actuator was again programmed to move at 0.1 mm peak-to-peak at 0.5 Hz. Figure 7 shows the experimental setup for this experiment.

After the data was recorded for both the cases, an FFT was performed on the data, and the result was plotted in Figure 8. From Figure 8, it can be seen that when the tag was placed on the actuator, the actuator's motion can be determined based on the peak. However, when the metal plate replaced the tag, the actuator's motion frequency did not provide a peak. This proved that the radar was able to reject the clutter.

3.2 Experiment 2: Motion of the tag in the presence of large motion from clutter

The second experiment was performed to validate the radar's clutter suppression ability when both the target and clutter were present in the same environment. In this case, the motion amplitude of the clutter was larger than that of the target. In Experiment 2, an actuator and a phantom were placed approximately 1 m away from the radar. The actuator with the tag was set at 1 mm peak-to-peak motion at 0.9 Hz while the phantom was connected to a metal plate larger than the tag size. After connecting the metal plate to the actuator, the phantom's motion amplitude was approximately 2 cm peak-to-peak. The phantom is a mechanical device that produces a complex motion with frequencies 0.2 Hz, 0.3Hz, 0.4 Hz, etc., similar to the breathing motion of a human. The phantom contains a metal plate and an oval disc. The motion is generated when the oval disc rotates and pushes the metal plate, causing a complex motion. Both the actuator and phantom were switched on at the same time, and their movements were recorded. Figure 7 shows the measurement setup for this experiment, and the result is plotted in Figure 9. The actuator's motion amplitude can be seen from the FFT plot, while the radar did not record the phantom's motion. Hence the radar was able to suppress the clutter motion.

4. CONCLUSION

The paper discusses the design of a 24/72 GHz harmonic radar to distinguish the target from clutter. The 3rd order based harmonic radar offers benefits such as higher isolation from the fundamental tone, smaller receiver and tag size, and avoiding the use of additional filters or diplexers over their 2nd order based harmonic counterparts. A passive tag was utilized as the target. Two experiments were performed to validate the clutter rejection ability of the radar. In the first experiment, target and clutter motions were recorded sequentially, while in the second experiment, the target motion was recorded in the presence of large clutter motion. The 3rd order harmonic radar was successfully designed and operated to detect the nonlinear device and reject clutter. This radar can be potentially used for suppressing background or clutter noise and can be used for detecting the authorized devices for security applications. The size of the radar is small compared to the above-discussed nonlinear radars. The future work of this radar is to operate the radar in ranging and localization applications.

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