Radar Cross Section Measurement and Performance Analysis using Signal Processing Techniques

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Abstract: In this paper an efficient numerical procedure for treating problems of Radar Cross Section (RCS) prediction of arbitrarily shaped Perfect Electric Conductor (PEC) objects is developed using frequency estimation algorithms. The frequency-modulated continuous-wave radar interrogation concept is based on Direct Digital Synthesis (DDS).It improves the resolution capability and accuracy of a radar signal. Surface Acoustic Wave (SAW) devices perform a radar measurement of the impulse response of the SAW transponder via a high frequency electromagnetic radio link. By analyzing the time delay between the backscattered pulses with different time delays we get a rough estimation of the RCS from the SAW transponder. The RCS are calculated from the scattered and incident fields. It is found from the simulation that the complexity of prediction can be reduced using proposed algorithm.

Keywords: *Micro-Electro Mechanical Systems (MEMS), Perfectly Electric Conductor (PEC), Radar, Radar Cross Section (RCS), Triangular Patch Model, Frequency Modulated Continuous Wave (FMCW), Dephasing.*

I. INTRODUCTION

Modern fighter aircrafts, ships and missiles need very low Radar Cross Section (RCS) designs, to avoid detection by hostile radars. Hence accurate prediction of RCS of complex objects like aircrafts is essential to meet this requirement. Moment and Finite Element Methods use the Electric Field Integral and Differential Equations are very useful tool for accurately predicting the Radar Cross Section (RCS) of arbitrarily shaped three-dimensional Perfectly Electric Conductor objects. In the arbitrary surface modeling the Field Integral and Differential Equation are complex for open and close bodies which requires advanced techniques. [1-2]. In the recent years the accurate measurement of RCS has been focused by many researchers and various method have been used.

Surface acoustic wave (SAW) delay-line sensors provide passive wireless interrogation for remote sensing and Identification. The SAW components can be tailored to be sensitive to several environmental variables because they do not require an external sensing element. This wireless sensor technology enables flexible measurement, monitoring of moving objects, and measurement in hazardous environments. In addition, the wireless interrogation of these passive sensors is possible in a range up to several meters, depending on the legal restrictions of the transmission power and antenna gain [6].Surface acoustic waves (SAWs) are ultrasonic waves propagating along the surface of the solids. It consists of 1) a small radio transmitter sending out a short burst of radio frequency waves, 2) a SAW based tag both receiving and modifying a portion of that signal and 3) a receiver to pick up the transmitted and modified pulse. The pulse variations are acoustically delayed and retransmitted from the antenna at the input port of the SAW. This delay influences the physical conditions like the velocity and amplitude, temperature, mechanical deformation or deposits on a surface. Hence it is possible to determine the influence by time measurement [4].

Reader systems for SAW transponders usually utilize the continuous wave(CW) radar principles.
Impulse radars could be considered but are inferior in cost and are not efficient in terms of feeding the electromagnetic energy in the transponder . Compared to systems operating in the visible or infrared light spectrum, FMCW radar sensors have excellent measurement range due to superior signal propagation [2]. FMCW radar systems can be mounted behind a wide variety of radio-transparent materials including most plastics and fiberglass. This allows for use in applications where the sensor must conceal for security, weather resistance or aesthetic reasons. FMCW radar systems continuously transmit, meaning that they are easily detected by electronic warfare systems.[23]

The FMCW radar is equipped with a fast direct digital synthesis (DDS) based frequency synthesizer that provides fast frequency sweeps. The phase locked loop (PLL) also been widely used in wireless communication systems due to the high frequency resolution and the short locking time. The DDS signal is mixed with the voltage-control oscillator output in the PLL feedback path is used for signal generation to achieve a very high-frequency resolution together with fast settling and spectral purity[23].

Today integration becomes the tendency in electronics. The flip-chip technology became applicable to SAW devices. Hybrid signal processing solutions were proposed to use this technology for bonding SAW devices onto a Silicon Application Specific Integrated Circuit (Si-ASIC) .This kind of hybrid chip includes digital and analog circuits; therefore a suitable hardware description language is necessary in order to model the whole chip. VHDL-AMS is a new hardware description language for analog, digital, and mixed-signal applications. The HDL Models of various blocks of DDS are described to predict the performance of the signals [8]-[9].

Discrete Fourier Transform (DFT) is used to estimate the parameters of a Reflected signal . Since the best performances of the DFT method are obtained when optimal choice of these windows is proposed. The parameter used for this purpose is the maximum sine-wave amplitude up to which the systematic errors are neglected compared with the quantization errors. Combined with windowing amplitude equalization improves the frequency resolution [17]

II. RCS MEASUREMENT USING SIGNAL PROCESSING ALGORITHM

Radar cross section (RCS) is a measure of power scattered in a given direction when a target is illuminated by an incident wave [4]. In other words, radar cross section provides an indication of how well a given target reflects radar energy. RCS is normalized to the power density of the incident wave at the target so that it does not depend on the distance of the target from the illumination source.

In designing stealth weapon systems such as military aircraft, control of their radar cross section is of paramount importance. Enemy missiles threaten aircraft in combat situations. One countermeasure which is used to reduce this threat is to minimize the radar cross section. Operators of communication satellites often request a complicated differential radar cross section in order to assist with the tracking of the satellite. The radar cross section measurement accuracy depends on accurate prediction of electromagnetic scattering from complex objects.

The idea of SAW remote devices emerged first for wireless identification systems. A SAW is a band pass frequency selective device that operates by converting electrical energy into acoustic energy in order to perform signal processing operations on the signal. These systems use a radio wave transceiver to interact with the sensors and so called ID tags [5].

A tag consists of a piezo electric crystal carrying interdigital electrodes that are connected to an antenna.The basic principle is that of interrogation device will send an RF signal[6] and it receive a modified response from an ID tag. The response from the tag will be modified in a manner proportional to the physical property being measured by the tag. The sensor tag varies its acoustically delayed radar cross section in proportion to the variable impedance loop connected to the SAWs output port. Variations in sensor impedance are caused by variations in physical properties to be measured.This in turn induces variations in the SAW filters acoustic impedance. The variations in the filters acoustic impedance lead to variations in reflectance for a received RF wave. The sensor tag varies its acoustically delayed radar cross section in proportion to the variable impedance loop [7].

Frequency or phase modulated waveforms can be used to achieve much wider operating bandwidths. Linear frequency modulation (LFM) is commonly used. In this case, the frequency is swept linearly across the pulsewidth, either upward (up-chirp) or downward (down-chirp). The matched filter bandwidth is proportional to the sweep bandwidth, and is independent of the pulsewidth frequency coefficient.

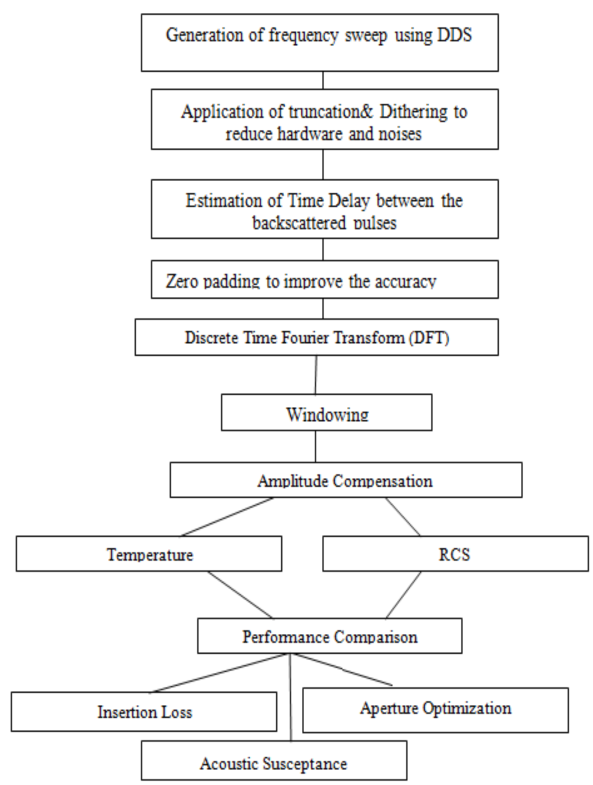

Figure 1: Flow Diagram of the Proposed Algorithm for prediction of Radar Cross Section

The difference component is in the order of few MHz. The difference between transmitted and received frequency is Doppler frequency. This gives speed of the given target (physical parameters). If the input frequency is higher for a specified bandwidth, it is easier to filter the sum frequency out of the signal so resolution improved.

III. SIGNAL PROCESSING

The generation of FMCW is essential to provide good linearity of the frequency sweep which must be extracted accurately. The DDS consists of a Phase Accumulator (PA) and a sine lookup table (LUT). The input to the phase accumulator is a frequency control word, which determines the periodicity of the phase accumulator. The PA is updated to the frequency control word or tuning word, at each clock, the output of the PA is fed to the LUT. The output of the LUT is then converted to an analog signal using a digital to analog converter.

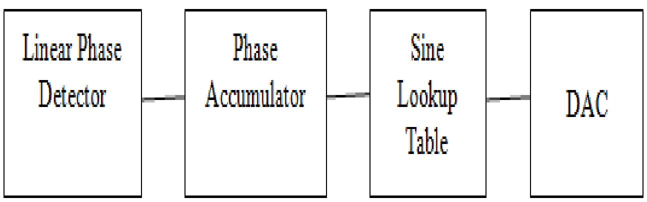

Figure 2: Block diagram of DDS for measurements of the signal response

The output voltage of phase accumulator is given as

$$fout = \frac{fclk}{2^n} \tag{1}$$

The size of the LUT depends on the length of the n-bit PA. If n is large then the LUT becomes too large, which is not desirable. This slows down the speed of the DDS and results in higher power consumption. To reduce the size of the LUT, a technique of phase truncation (PT) is employed. To reduce the size of hardware the phase to sine look up table is dividing into sine and cosine functions using Jordon's Algorithm. System Generator DSP design tool from Xilinx combined MATLAB simulink provides a VHDL-AMS design for DDS.

According to Frequency Modulated Continuous Wave (FMCW) radar principle ,the received signal is time delayed by the RTDT $\tau = \frac{2d}{c}$ with c denoting the speed of light, and d is the round trip delay caused by a target in distance d,

$$x_r(t) = A_t \cos\left[2\pi f_0(t-\tau) + 2\pi\frac{k}{2}(t-\tau)^2\right] \tag{2}$$

If the transmitted signal is of the form

$$x_t(t) = A_t \cos 2\pi\left(f0 + \frac{k}{2}\right)t \tag{3}$$

where $k = {}^{B}\!/_{T}$ is the steepness of the chirp.

After reception the two signals are mixed and a digitized signal is produced at the output of the mixer. If p targets are present the signal at the output of mixer is a sum of cosines and is given by

$$x[n] = \sum_{i=1}^{p} A_t \cos(2\pi\psi_i t + \phi_i) \tag{4}$$

where $\psi_i = 2\pi f_0 \tau_i$ and $\phi_i = \frac{B}{N}\tau_i$, N is the number of samples.

The method for determining τ is to estimate the frequencies of the cosines of (2) by the DFT (Discrete Fourier Transform).Previous to the fourier transformation the data is padded with zeros, equal to the sample length of DFT.This zero padding is necessary to improve the accuracy of the estimated frequencies. To ensure resolution of individual targets the side lobe level low, a proper windowing function should be applied to the row of data.

The Discrete Fourier Transform $x[k]$ is generally defined as

$$x[k] = \sum_{n=0}^{N-1} x[n]\exp\left(-j\frac{2\pi}{N}kn\right) \tag{5}$$

This summation should run from $-{}^{N}\!/_{2}$ to $({}^{N}\!/_{2}-1)$ .This shift in the summation index produces a time shift in the sampled data and leads to a fast rotation in the phase of the DFT output.

This is improved according to

$$x_{DP}[k] = x[k]\exp\left(-j2\pi i\,{}^{N}\!/_{2N_{FFT}}\right) \tag{6}$$

N corresponds to the sample length & N_{FFT} is the length of the DFT result [9].

VIII. RESULTS AND DISCUSSION

The proposed algorithm has been implemented using reflectors and the necessary analyses and measurements has been taken. Figure 6 shows the magnitude response of SAW sensor with three reflectors placed on the tag.

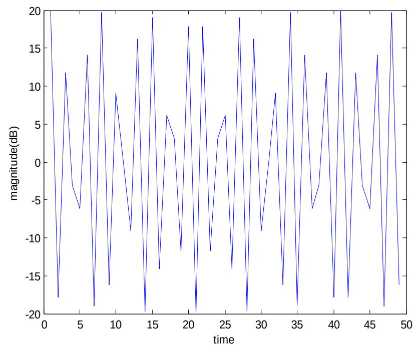

Figure 3: Magnitude response of saw sensor with three reflectors placed on the ID tag.

From the reflectors placed on the interdigital transducers the reflected signal responses are analyzed with their magnitude responses and plotted with respect to the time period. For the analysis purpose the first reflector output signal in terms of magnitude signal with respect to time period is considered.

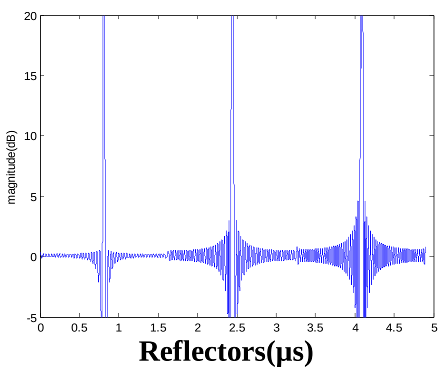

Figure 4: Range profile for the SAW sensor with three reflectors

The reflected signals responses are compared with their magnitude responses of the incident signal values and measuring with their time response signals. Here Fig.7 considering the three reflectors time response signals and their performances are compared with their magnitude values.

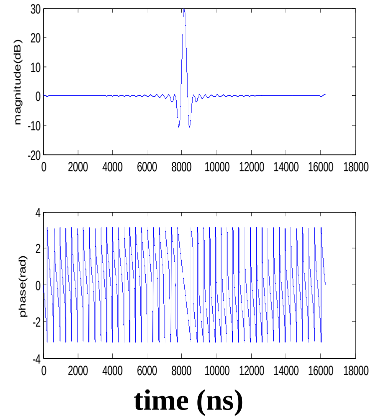

Figure 5: Measured time and phase response for a wireless SAW sensor using DFT implementation.

From the Figure 8 the reflected signals magnitude and phase values are represented corresponding to the time in nanoseconds. The peak values present in the reflector will make the time delays in the phase value of their corresponding reflectors.

The attenuation of the reflected signal in terms of temperature is shown in Fig 9. A linearity of 2dB per 100K is observed from 0°C to 100°C. From the figure the temperature value increases automatically the attenuation value increases.

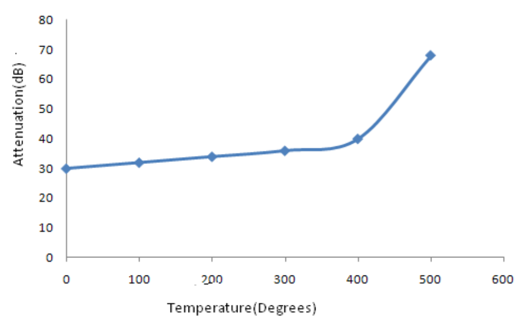

Figure 6: Variation of Signal attenuation with Temperature

The resolution of the sensor can be enhanced by increasing the bandwidth through adding zeros to the measured data.

Round trip delay time(μs)	Zero padding with 2^8 points	Zero padding with 2^{10} points
0.9	1.67675	1.67663
4.7	1.67677	1.67676
5.4	1.67655	1.67669
7.4	1.67680	1.67675
8.2	1.67655	1.67553

Figure 7: Variation of signal attenuation versus temperature

To suppress the leakage of the dominant reflection the window function has to be chosen properly.eg. with Blackman harris window. In order to find the time delay and phase of the system accuracy we will assume the sample length N=1024

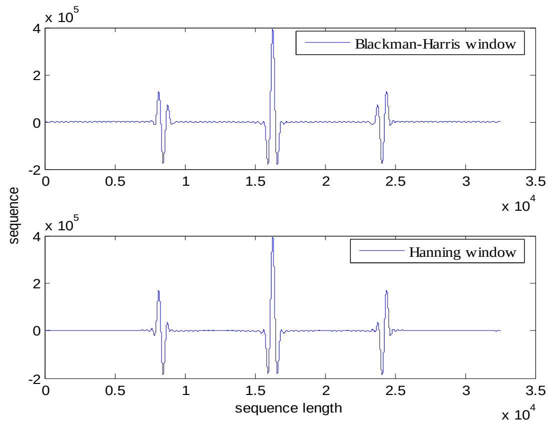

Figure 8: Correlation between the measured time responses of the reflectors with different window functions are represented

Time(μs)	Phase angle of a DFT input signal	Phase angle after applying Dephasing
0	0	-1.9539
0.092	-2.6664	1.6630
0.0002	-2.3123	2.0171
1.6000	-2.3780	1.9513
0.500	-0.5518	-2.5057
0.0005	-0.4757	-2.4296
0.01	1.9931	0.0392

Figure 9: Measured phase angle at different time instances before and after dephasing with NFFT=16183

From the figure 12 the measured phase angle of the reflectors are represented with different time instances. The phase angle values are estimated with DFT for the analysis of RCS. Before applying the Dephasing signal and after the dephasing signals are estimated and represented with time period in microseconds.In this section numerical results are presented for wide band RCS of cube, sphere and cylinders. These results have excellent correspondence with results obtained via earlier approaches [7]. The Radar cross Section of Cube is estimated from the incident signal with the reflected or scattered signal. The RCS is calculated by dividing the object into 48 triangles of the batches to get the reflected signal accurately.

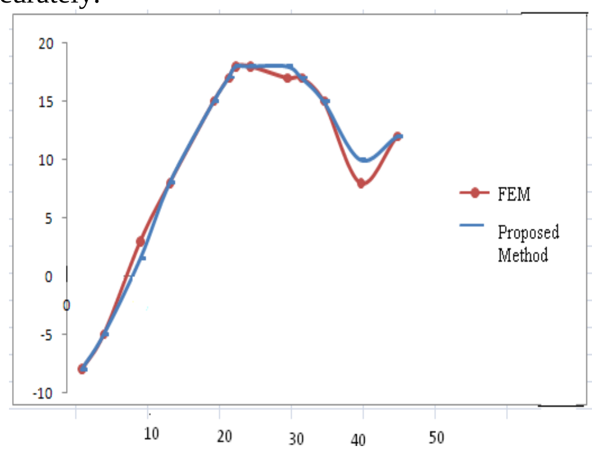

Figure 10: Radar Cross Section of Cube

The RCS of Sphere was calculated from the proposed method by dividing the corresponding object into 500 triangles of patches to find out the reflected signals accurately. This output values were compared with their existing methods.

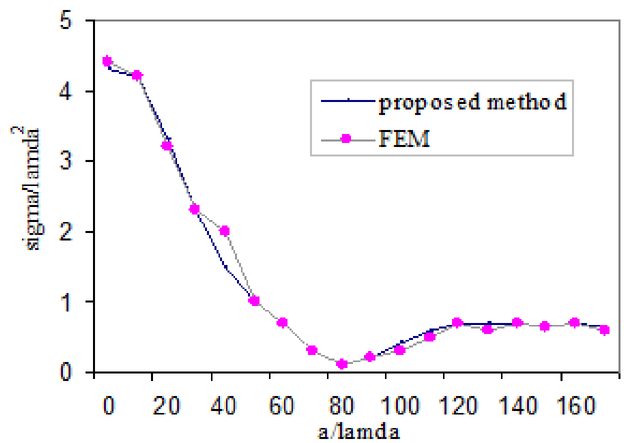

Figure 11: Scattered cross section of Rectangular Cylinder

From the above figure the RCS of the Rectangular cylinder is estimated is represented with respect to the lamda values. The proposed method values of RCS are compared with the method called finite element method. Both methods were compared and the proposed method gives a good accurate value of RCS compare to FEM.

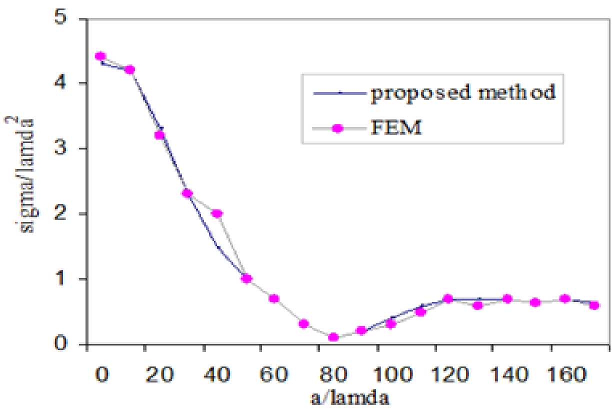

Figure 12: Scattered cross section of Circular Cylinder

CONCLUSION

By combining the principles of wired SAW sensors with the radio request technique, known from SAW ID tags, readout of passive sensors solely by using a radio frequency link can be developed. Based on a commercially available readout system developed for identification applications and some corresponding SAW ID tags, we built up a wireless system for measuring RCS. In the first step we evaluated the delay time difference between the first three impulse responses of the investigated SAW ID tags which gives a first rough estimation allows us to overcome the limited RCS range of the phase evaluation. The proposed algorithm can be used to reduce the dimensionality of the problem, and the ability to model infinite domains accurately. The model developed can be used to simulate dipole mode for complex shaped objects.

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