ISSN 2394-3777 (Print)
ISSN 2394-3785 (Online)
Available online at www.ijartet.com

International Journal of Advanced Research Trends in Engineering and Technology (IJARTET)
Vol. 4, Special Issue 6, April 2017

Discrete-time signal processing for estimation and measurement of low dopplerusing CW ultrasound :Advantages and Limitations

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***Abstract*—thispaper focus onto the method of Doppler measurement of small vibrations using ultrasound signal.This paper contains the details of anestimation and experimentwith a hybrid signal processing method for the detection of low Doppler in the presence of wind and undulations of terrain. It is a non-contactingvibration sensing method for the application on moving vehicles. The Doppler can be extracted from the phase deviation of the received ultrasound signal. In this system the estimation and measurement was done using a 200 KHzsignal at a sampling rate of 2MSPS having sixty ultrasound channels. This paper has been mainly divided into three parts,estimation, simulation and measurement.**

Keywords—ultrasound;doppler;statistical signal processing, parametric spectrum estimation, field programmable gate array.

I. INTRODUCTION

Doppler measurement isone of the methodsused for vibration measurementand analysis. The proposed vibration measurement system is intended to measure buried vibrating objects by detecting the Doppler shift on the ultrasound wave that is scattered by the vibrating earth surface and other structures vibrating with reference to the ultrasound transducer.The measured value may be used to characterize different buried objects in earth. Here we are trying to find answers to the following questions related with this topic.

1)"What actually limits minimum measured value in the implementation of digital ultrasound Doppler measurement system?".2)"How to improve non contact sensing mechanism using digital signal processing methods?".3)"How to characterize different buried objects?".4)"Is it possible to extract reliable vibration information, in the presence of wind and undulations of terrain?".5)"How to compare phase deviation with acceleration in g".

II. THEORY – ESTIMATION AND SIMULATION

A. Basic Theory

The angular deviation (Doppler) caused by vibration is directly proportional to the amplitude of the incident signal, surface displacement, incident signal frequency, incident angle & reflected angle and is inversely proportional to sound velocity in the medium. Thepresence of terrain undulation and variations in medium due to environmental factors such as wind causes spatial de-correlation and distortion in thevibration. The related equations are

$$x(t) = A_c \sin[\omega_c t + m_f \sin(\omega_m t + \phi_m) + \phi_c] \qquad (1)$$

where $x(t)$is the reflected signal.A_c is the amplitude of the reflected signal.$\omega_c$is the center angular frequency of ultrasound signal and $\omega_m$is the angular frequency of modulating signal.ϕ_c is the phase shift due to wave propagation. m_f is the modulation index due to Doppler effect, and is given by

$$m_f = \frac{2\omega_c A_m}{c} \qquad (2)$$

c = sound velocity in air.

In order to detect the angle deviation, the following reference signals are to be convolved with$x(t)$.

$$V_{refI} = A_{ref} \sin(\omega_c t) \&$$
$$V_{refQ} = A_{ref} \cos(\omega_c t) \qquad (3)$$

After convolution, filtering and phase measurement $(\tan^{-1}(Q/I))$ can retrieve actual vibrationsignal having mathematical form of$m_f \sin(\omega_m t)$.

B. Estimation in the presence of Noise

The equation (1) can be written as $y(t) = x(t) + e(t)$ where $e(t)$ is assumed to be complex valued additive noise. x(t) is equal to noise free complex valued sinusoidal signal as defined in the eq (1). It is re-written as the form

$$x(t) = \sum_{k=1}^{N} \alpha_k e^{i(\omega_k t + \varphi_k)} \qquad (4)$$

$\alpha_k, \omega_k, \varphi_k$ are its amplitudes, angular frequencies and initial phases respectively.

In real situation the complex signal indicates presence of sine (in-phase) and corresponding cosine (quadrature) components. The variance (power) of noise is $\sigma^2 = E\{|e(t)|^2\}$. The noise is assumed as white for initial estimation. In our method continuous time counterpart of noise is correlated for a small duration of expected signal to avoid aliasing and results in white discrete time noise sequence. In real situation the noise is not white and has unknown spectral shape, hence accurate frequency estimate can found using nonlinear least squares (NLS) method [5]. The basis of the method is to approximate the model by a linear one and refine the parameters by successive iterations.The signal amplitudes then adjustedto give corresponding local signal to noise ratio (SNRs) at eachfrequency. The amplitude adjustment is similar to that of a noise whitening and filtering.

Consider the signal in (4), here we are assuming that, angular frequency,$\omega_k \in [0,2\pi]$. Otherwise we have to deal with phase ambiguities. In real situation to maintain this condition, it is required to lock the phase and track it accordingly. The initial phase φ_k is also assumed to be independent random variable uniformly distributed over$[0,2\pi]$.Now the correlation and the distribution of power over frequency (Power spectral density-PSD) can be measured by means of either nonparametric or parametric signal processing techniques.

In non parametric (classical) method the signal usually fed to a bandpass filter with a narrow bandwidth and filter output power divided by filter bandwidth is used as spectral content. The parametric method postulates a model for the input data and provides a means for parameterising the spectrum and thereby reduces the spectral estimation problem to that of estimating the parameter. However in realscenario the input data may not satisfy the assumed models in some situations. In this case the nonparametric methods may outperform the parametric method. Hence in real-time product development ahybrid methodis a better method. In this work we have used a parametric method with continuous modeling and non-parametric method concurrently. The proposed hybrid method is also efficient in the implementation.

One of the methods for non parametric estimation is using fast Fourier transform analysis (FFT) and for parametric estimation is autoregressive(AR)spectral estimation.The Fourier technique is defined for finite energy periodic signals for infinite duration and the methodused FFT has some limitations, as the way of improving spectral resolution is by taking longer frame.The AR model contains parameters which can be estimated from the Doppler data. The estimation of these parameters for the AR model results in linear equations, which can be implemented easily. The AR model is equivalent to a maximum entropy(ME) model and the spectral estimate based on the ME model has the extremely important property that it is optimally smooth [3].i.e. it maximizes the randomness of the unknown time series, producing the flattest spectrum consistent with data. The principle of maximum entropy states that the probability distribution which best represents the current state of knowledge is the one with largest entropy. [4] discussed about Improved Particle Swarm Optimization. The fuzzy filter based on particle swarm optimization is used to remove the high density image impulse noise, which occur during the transmission, data acquisition and processing.

In our method we have used both parametric and non-parametric method to solve the problem.

a. Optimized NLS method: using Phase accumulation & correction algorithm and curve fitting algorithms.

b.Non parametric estimation: 512 tap BPF filter and 512 point FFT using Cooley–Tukey FFT algorithm.

c. Modified parametric measurement : Frequency boosting algorithm.

C. Practical considerations

A real time maximum entropy autoregressive spectrum analyzer capable of analyzing Doppler signals has been described by Sclindwein and Evans. Here we are using a new hybrid method, a combination of parametric and non-parametric method for measuring low Doppler distorted by thepresence of terrain undulation and wind for different classes of objects (sinusoidal signals corrupted by colored noise). In order to convert continuous analog data to discrete signal an analog to digital converter is to be used by compromising for quantization error. A “N” bit analog to digital converter has a resolution of 2^N. The minimum value determines minimum detectable phase deviation caused by Doppler.Minimum detectable phase deviation is $10/2^{N-1}$. Fig 4 shows simulated result which uses 12 bit resolutionfor phase deviation of 0.01 degree.

Different objects cause different surface displacement for various frequencies. Hence these objects can be characterized based on their responds for complex frequencies. In this experiment we are considering five different objects ITM, SM, BM, APMBK, and APMBR and a signal generated using five different frequencies (F1, F2, F3, F4 and F5). The signals were generated and processed by the relative algorithms and periodicity is maintained by transmitting continuous signal. The algorithm detects continues phase variation due to Doppler. Equations for conversion between phase angle, vibration amplitude and acceleration in millig is given in (5).

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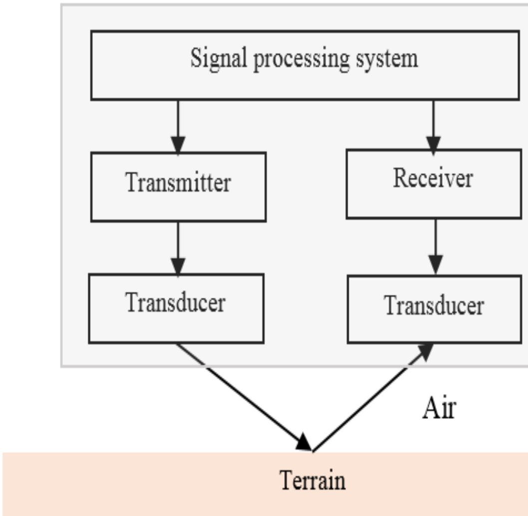

Fig.1. Functional diagram.

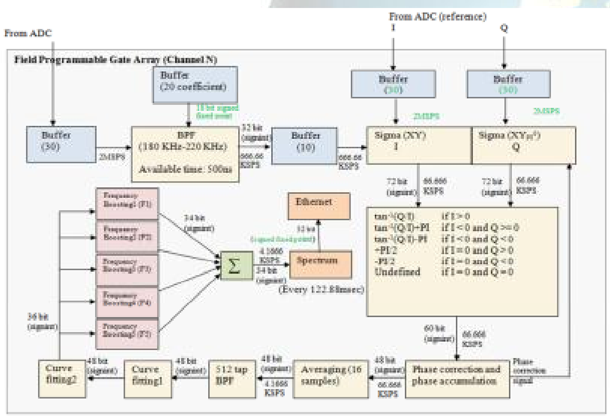

Fig.2. signal processing algorithm for estimation of amplitude of vibration of buried objects from reflected ultrasonic waves.

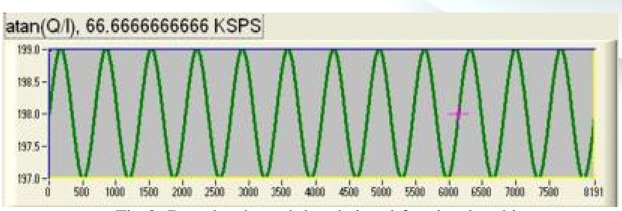

Fig.3. Doppler demodulated signal for simulated input.

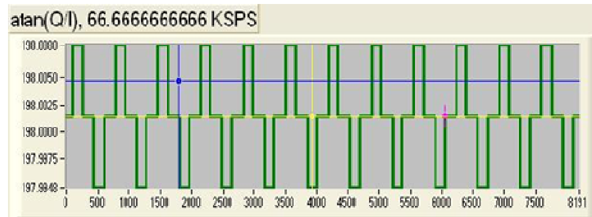

Fig.4.Minimum measured value due to quantization of ADC.

$Wavelength, \lambda \;= c/f$

$m_f{}^{c} \;= \left(\sqrt{\frac{\mathrm{PSD}}{2^{31}}}\right)(3.6/2.414)$

$m_f{}^{o} \;= (m_f{}^{c}\,360)/(2\pi)$

$\mathrm{r} \;= (\lambda/360)\phi^{o}$

$\omega^2 \;= (2\pi f_n)^2$

Accelerationin mg= $(\omega^2 r)/(9.8\,X\,1000)$. (5)

PSD = Measured power spectral density.

$m_f{}^{c}$= phase deviation in radian.

$m_f{}^{o}$= phase deviation in degree

r =vibration amplitude.

III. MEASUREMENT

The measurement was carried out using ultrasound transducers, pre-amplifiers, signal generators and processing elements. The sixty channel discrete data were collected using a FPGA into a circular buffer. The signal processing was done using DSP slices of FPGA. The process contains filters, controlling algorithms for tracking phase deviation in the presence of terrain undulation &wind and hybrid power spectrum density measurement techniques. Fig 5 shows measured value for 0.02 degree deviation, it then processed to get better signal as shown in fig6.

Fig 7 shows a frequency response of 512 tap FIR Band pass filter and frequency boosting algorithm. This algorithm outperforms a traditional BPF by utilizing fewer resources and minimum delay for mathematical computations in the FPGA.

In order to achieve reliable characterization the system utilizes prior knowledge of required parameters such as received signal amplitude on each sensor, percentage of variation in vibration on-specimen and off-specimen and real-time variation of received signal due to external factors.

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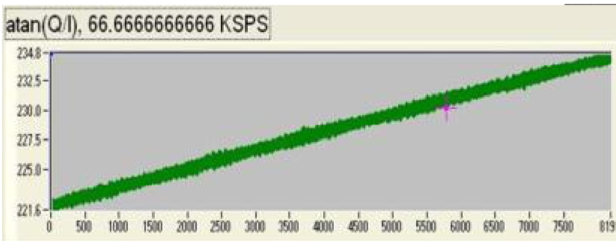

Fig5: Measured value for 0.02 degree actual signal

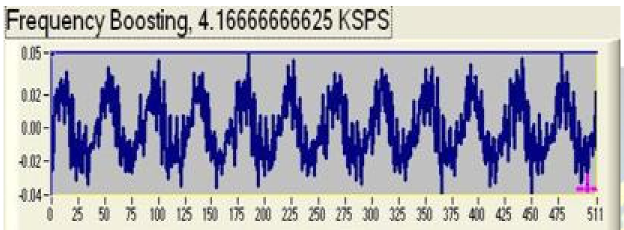

Fig6: After discrete time signal processing for 0.02 degree

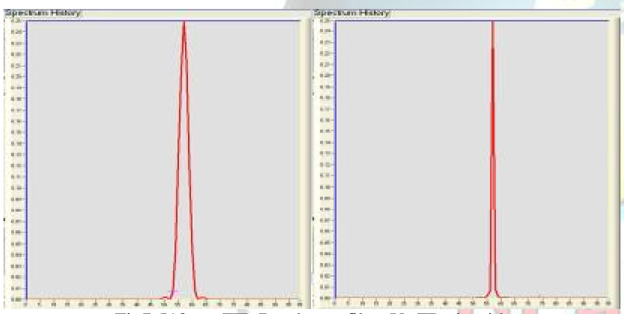

Fig7:512 tap FIR Band pass filter Vs FB algorithm

Fig8: FPGA based sixty channel digital signal processing system.

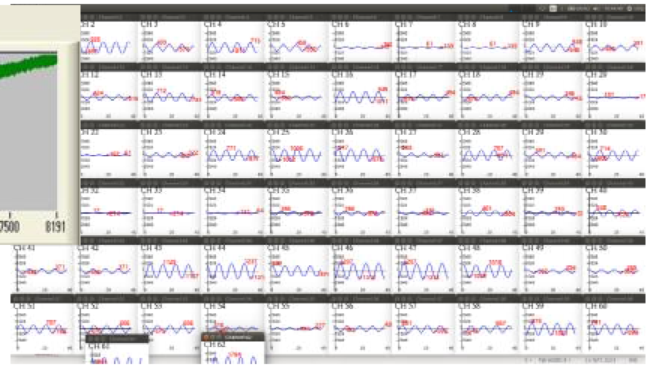

Fig9: Sixty channel realtime data analysissoftware.

TABLE I. CHARACTERIZATION

Frequency	Ambient Noise	Specimen				
		ITM	SM	BM	APMBK	APM2BR
F1	65	95	94	126	57.6	54.4
F2	35	68.8	62.4	154	42.8	28.8
F3	30	52	23.6	98	27.2	27.6
F4	10.4	NA	NA	NA	20.8	26.4
F5	9	NA	NA	NA	12	24.4

Table-1 shows characterization of specimens ITM, SM, BM, APMBK, and APMBR and using frequencies 97.65625Hz (F1), 146.484375 (F2), 195.3125 (F3), 244.140625 (F4) and 341.796875 (F5).

IV. CONCLUSION

Investigations on performance and implementation aspects on signal processing algorithms conducted and the following conclusions drawn from this study.The main aim of this work was to find answers to the questions given in the introduction and they were answered with theoretical and practical approach as described above. It is summarized as below.

1) "What actually limits minimum measured value in the implementation of digital ultrasound Doppler measurement system?" Ans:It is the resolution of analog to digital converter.

2)"How to improve non-contact sensing mechanism using digital signal processing?"

Ans:In this work we have triedcombination of parametric and non-parametric signal processing power spectral density estimation methods. They have considerable improvements.

3)"How we can characterize different buried objects?"

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Ans: Each objecthas its own responds towards different frequencies. More study and parameterization is required for reliable characterization.

4)"Is it possible to extract reliable vibration information, in the presence of wind and undulations of terrain?" Ans:Not fully. But with the use of real-time data analysis, real-time datamodeling, FPGA based platform and parameter estimation methods improvement is possible.

5)"How to compare phase deviation with acceleration in g". Ans: Equation (5)

Future scope of this work includes the development of algorithms andadvanced non contact vibration analysis systems for detecting buried landmine[7], micro-doppler[8]and will also use in systems needs vibration analysisusing non contact methods. The proposed system can contribute to Non Destructive Testing.

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