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Flaw Detection using Split Spectrum Technique

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ABSTRACT:Flaw detection is a common application of industrial ultrasonic testing. The propagation of sound waves through materials has been used to detect discontinuities within them. Sound waves reflect from flaws in a way that can produce distinguishable echo patterns. Thus the presence of flaw within materials can be determined. In addition to the flaw echo, reflections from microstructure contribute to reverberation, which interferes with the signal. Reverberation is expected to have complex interference structure. This interference pattern varies with the transmitted frequency. To take advantage of this phenomenon, a wide band signal is transmitted to effectively reduce the influence of reverberation. So it is assumed that the reflections from the flaw is insensitive to frequency and produces a steady output. This property has been utilized for flaw detection. Eliminating the unwanted reflections using conventional filtering techniques removes the flaw signal also, since both the received echo and reverberation are generated from the same transmitted signal itself and has similar spectral distributions. So, it has been proved that Split Spectrum processing algorithm followed by Order Statistic Filter can provide an optimized result. Multiple pulses will betransmitted and Order Statistic filters can be used for post processing of the received pulses. Thus, by processing the multiple echoes corresponding to a set of transmitted signals, the effect of microstructure reflections can be suppressed with respect to the flaw echo.

Keywords:Flaw Detection, Wide-band signal, Order Statistic Filters, Split Spectrum Processing.

I. INTRODUCTION

Non-destructive testing is a technique to find the quality of a material or structure without doing harm to the specimen under test. There are many non-destructive testing methods to find the deformities within materials. Of them, ultrasonic testing is more effective, as ultrasound can penetrate more deep into the material under test. The basic principle is that when an ultrasonic pulse is transmitted through the material, it propagates down the material and if a flaw is present, part of the energy is reflected back due to the discontinuity in the medium. This reflected signal (echo) is received and processed to find the presence of the flaw. The location of the flaw can be found from the time difference from the transmitted pulse and received echo. The processing of the echo is hampered by the presence of spurious reflections from many smaller discontinuities in the material i.e., the microstructures within a range cell, defined by a distance cT/2, where c is the speed of sound in the medium and T is the transmitted pulse length.

The signal from a range cell contains the echo from the flaw as well as many random reflectors such as grains which makes the detection of flaw difficult as both the echo and the grains will have same spectral characteristics. The echo to grain ratio can be improved by changing the portion of the transmitter receiver transducer at different locations and averaging the signals corresponding to different locations [13]. An alternative technique used in radar when targets are embedded in smaller random targets known as clutter (same as grains) is a technique known as frequency diversity or agility. This is achieved by transmitting many channels with different frequencies or by shifting the transmitted frequency between pulses. The de-correlated received clutters signals are then averaged which results in improved signal to clutter ratio. The use of broadband transducer and a broadband transmitted signal consisting of many narrow band signals was introduced in [13]. The resulting echoes are subsequently averaged to get improvement in flaw to grain echo ratio. To employ this frequency diversity concept, a wide-band signal is transmitted.

In this paper, a wide band signal is transmitted and the flaw enhancement will be achieved by the use ofSplit Spectrum processing algorithm followed by the post-processing using Order Statistic Filters. In this, the received broad band

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signalis split into many continuous narrow bands by digital filter banks. It is based on the assumption that the super position of many scattering points from a range cell; is frequency sensitive, meaning that the grain noise will be different for different bands. The sub-bands are separated by more than the inverse of pulse length. The grain echoes will, be de-correlated while the flaw echo remains constant across the bands. The correlation between the observations can be reduced by reducing the bandwidth overlap of each channel. The de-correlation effect on the grain echoes is due to the effect of complex interference of different frequency components of the wideband signal adding with different phases. The filter bank is realized using DFT.

Analysis of the signal spectrum of reflections caused by microstructure of the material under test will show that most of this signal energy lies within the same frequency band as the flaw (target) signal energy. So flaw detection becomes difficult. Conventional filters (such as using a low pass, high pass, band pass filter or averaging)are not found to be successful. Any such filter designed to eliminate the microstructure signal also eliminates the flaw signal. SSP(Split Spectrum processing) followed by Order Statistic Filters helps in the reduction of microstructure signal while enhancing the flaw signal visibility [5]. The popularly usedpost detection processors are the n-pulse integrator and binary integrator [6]. n-pulse integrator is the oldest technique in post processing. It averages the return signals of the multiple transmitted signals to reduce the noise. Binary integrator applies two thresholds, one at the input and another at its output. It counts the number of times the return signal exceeds a threshold and the number of times the first threshold was exceeded, is compared to another threshold for the decision purpose. The OS (Order Statistic) filter is equivalent to the binary integrator when a threshold is applied to the output of the OS filter.

II. LITERATURE SURVEY

In 1976 [9] Nihat M Bilgutay et al, developed a random flaw detection system with enhanced signal to noise ratio by utilizing correlation and time integration techniques. The proposed system is advantageous for highly absorbent materials and to detect smaller flaws at greater distances. The system is superior when compared to the conventional techniques that were present at that time, like the pulse-echo flaw detectors. But the system is not efficient when clutter noise is present, which is due to the grain structure of the material. In 1981 [10] N.M.Bilgutay et al, describes a flaw to grain echo enhancement technique called split spectrum processing which improves the flaw to grain echo ratio in large grained materials. The technique suppresses the grain echoes using a novel minimization and conventional averaging algorithms. Frequency diversity concept is used here as in radar systems. The ability of order statistic filters to perform post detection processing in various target and clutter environments, is explained [6] .The performance of two popular post detection processors like n-pulse and binary integrators are compared. Each has its own superiority with respect to the shapes of the target and clutter distribution functions. In 2011 [4], J. Saniie.et al, presented an FPGA based system to perform the target detection for real time ultrasonic imaging. The use of FPGA made the Split Spectrum algorithm flexible and robust. This enabled the evaluation of the implementation impact caused by parameter changes(such as number of band pass filters, bandwidths, etc) in the Split spectrum processing algorithm.It is shown by Krauss and Goebbeb as in [13] and Kennedy and Woodmansee as in [7] that the echo to grain ratio can be improved by changing the portion of the transmitter receiver transducer at different locations and averaging the signals corresponding to different locations. This is based on the effect of grain echo de-correlation resulting from the shift of the transducer.An alternative technique used in radar when targets are embedded in smaller random targets known as clutter (same as grains) is a technique known as frequency diversity or agility. This is achieved by transmitting many channels with different frequencies or by shifting the transmitted frequency between pulses. The de-correlated received clutters signals are then averaged which results in improved signal to clutter ratio.Krauss and Goebbeb as in [13] extended the concept of frequency diversity and proposed the use of broadband transducer and a broadband transmitted signal consisting of many narrow band signals. The resulting echoes are subsequently averaged to get improvement in flaw to grain echo ratio. To employ this frequency diversity concept, a wide-band signal is transmitted.

III. PROPOSED ALGORITHM

Split spectrum processing (SSP) utilizes the idea of frequency diversity approach by using one wideband signal and then splitting the spectrum into separate sub-bands using a filter bank. These sub-band signals are then combined, usually by some nonlinear operation, into a filtered signal, to get the final output.

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The receiver uses a Split Spectrum Processing algorithm. Here, the received signal is cross correlated with the reference signal and its spectrum is found by FFT. This spectrum is split for post-processing, refer Fig-1. In the received signal, microstructure reflections(reverberation/clutter) and flaw reflections(echo) lie within the same frequency band.Conventional filtering when clutter is present does not improve SCR because signal and clutter are correlated.

In the received signal spectrum, echo remains constant while the reverberation significantly varies due to the interactions of the random phase and the amplitudes of the different frequencies contained in the signal. But the echo signal from the defect will contain spectral energies over a wide frequency band. So there will be no significant variations for the echo signal from the target. This property is exploited in the processor -SSP combined with Order Statistic filters, to provide improved output signal to clutter ratio.

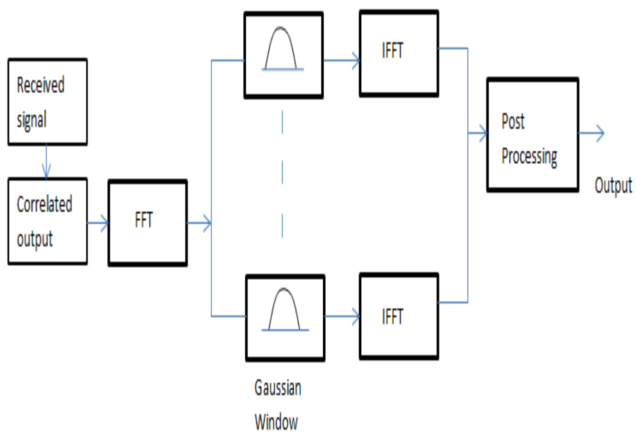

Fig.1 Split Spectrum Processing Algorithm followed by post processing

SSP involves in decomposing the received wideband signal into a number of sub-bands. By splitting the spectrum, we will be able to observe the variation of the reverberation in all sub-bands. But the target signal will not have any variation. The target signal will have almost the same power. So some bands have large variation and some have almost the same signal level. This property is used to enhance the target signal with respect to the reverberation.The sub-band signals will be then processed by applying a non-linear selection technique like Order Statistic filters. This type of filtering can retain signal information only when there is a strong correlation among most of the sub-bands at a given time instant. The Fast Fourier Transform is used for frequency analysis of received signal. The performance of SSPdepends upon the number of band pass filtering channels, the correlation between the different observations, and statistical information in each channel. Increasing the number of channels increases the likelihood of separating flaw and grain echo information. In order to enhance the visibility of flaw echo concealed by clutter, SSP method employs a post-processor for combining all the incoming information from sub bands. This post-processor reconstructs the time-domain signal with the objective of obtaining maximum flaw-to-clutter ratio (FCR). Several types of processors can be used to extract the flaw echo information. Minimization technique, which comes under Order Statistics, can be effective in suppressing the clutter echoes when flaw echo information exists in all the observation channels.

Steps employed for the proposed algorithm:
1. Correlation of the received signal s(n) and reference signal u(n) will be taken.
2. Frequency spectrum of correlated output will be taken using FFT.FFT is proposed because it is simple and easy to perform.
3. Spectrum will be split into several narrow sub bands. Multiplying with Gaussian window can split the spectrum.
5. Finally, these outputs will be fed to a post processor .This block will analyse the filter outputs for the presence of flaw signal. Post processing can be done by calculating the threshold and comparing it with the filter outputs from each channel. If any of the channel output exceeds the threshold value, presence of flaw can be confirmed.

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IV. SIGNAL AND RECEIVER MODEL

In order to study the receiver structure and its performance, the transmitted and the received signals are modelled as follows. Since we expect the reverberation to have complex interference structure, many frequencies need to be contained in the transmitted signal. A wide band signal can meet this requirement. The reverberation is simulated as a sum of reflections from individual microstructures with random phase shift and random amplitudes. The received signal is assumed to be the sum of the delayed and attenuated transmitted signal and the reverberation isgenerated as above. Band limited Additive White Gaussian Noise is also added.Refer Fig – 2.

The transmitted wide band signal is simulated as a sum of sinusoids by the time domain relation:

$$u(n)=\sum_{i=1}^{n} s(fi); \quad fi= 200Hz\ldots.. 400Hz\text{--- Equation 1}$$

wheren is the number of signals, fi ranges from 200 to 400 Hz. u(n) is the transmitted wide band signal which is the sum of the 'n' signals. For this signal we assume that there is no phase shift and random amplitudes.

The reverberation is simulated in a similar way butwith random phase shift (exponential term) and random amplitude (for the cross section of the microstructure). The reverberation is simulated using the relation:

$$Y(f)=\sum_{i=1}^{m} Ai * R(f - fo) * e^{-j2\pi f\gamma i}\text{--- Equation 2}$$

Where A_i, represents the random amplitude of the random scatterers(grains), *m* represents the number of scatterers, f is the transmitted frequency, f_0 is the frequency shift due to scatterers. R(.) is the Fourier Transform of the cross correlation between the transmitted and the received signal and Y(f) is the Fourier transform of the simulated reverberation.

The received signal s(n) is the sum of the weighted and delayed transmitted signal u(n), reverberation y(n), and Additive White Gaussian Noise , w(n).

$$s(n)= \alpha*u(n-\gamma) + a*y(n) +b*w(n)\text{ --- Equation 3}$$

where α, a, b are weighting functions, y(n) is the inverse Fourier transform of reverberation Y(f).Four range cells are assumed and the target is fixed on the second range cell.

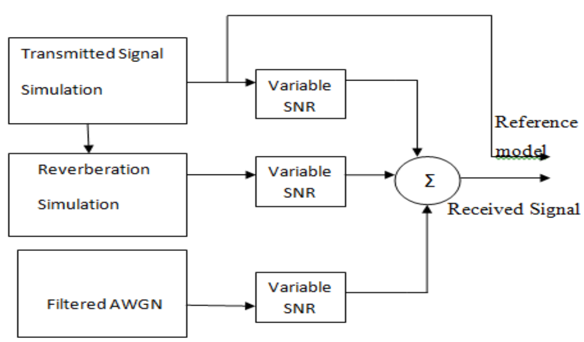

Fig.2 Basic block diagram showing reference and received signal generation

For the simulation of receiver, refer Fig - 3, the correlation between the received signal and the target signal will be takenin each range cell. Then the Fourier transform of the correlation output was taken. Then the spectrum was split into consecutive bands and a Gaussian window is applied to each group of the split spectrum group and inverse Fourier transform is taken to get the band pass filter outputs .

These outputs are fed to post processing. For all range cells, variance of each channel output is computed. These outputs are squared and minimum of these values will be taken from each channel. The minimum of all the variance values so obtained will be used to find the threshold. The threshold will be chosen such that it is twice the variance

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selected. This threshold so obtained will be compared with variance values obtained from each range cell to find the presence of the flaw. For any range cell, if the variances obtained exceed the calculated threshold, presence of the defect can be confirmed.

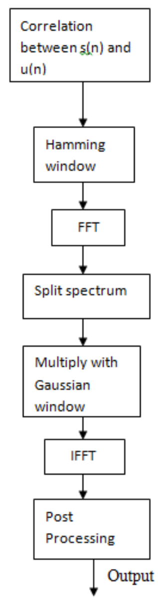

Fig.3 Receiver Simulation

V. POST PROCESSING USING ORDER STATISTIC FILTERS

In signal processing, nonlinear filters like order statistic filters have enabled signal processors to enhance the corrupted digital information. Minimization, median, and maximization processors all fall under the category of order statistic (OS) filters that have been readily developed in the statistics field, and have found application in radar, sonar and image processing.

In signal processing with respect to flaw detection, the order statistic filter is proposed which operates on a set of n simultaneous sample values, $(X_1, X_2, X_3, \ldots X_n)$ corresponding to the n channels of the SSP (Split Spectrum processing) output. These n values are ordered according to amplitude to produce the sequence as given below:

$$X_{1:n} \leq X_{2:n} \leq X_{3:n} \leq \ldots X_{n:n} .$$

A quantile is a value from a set of values that will divide the probability distribution function into equal probability regions. OS is shown to be a biased estimator of the quantile as explained in [3]. The input signal of the OSfilter x_i are considered to be independent and identically distributed with distribution function $F_X(x)$, the probability density function for the output, is given by a result in order statistics [3] as given below :

$$f_{X_{r:n}} = r \binom{n}{r} F_X^{r-1}(x)\left(1 - F_X(x)\right)^{n-r} f_X(x) \text{ --- Equation 4}$$

$f_X(x)$ is the input probability density function. ‘x’represents the real value of the observations of the input sequence and $x_{r:n}$ is the real value of ordered sequence, while X is the random variable for the input of the OSfilter and $X_{r:n}$ is the random variable for the ordered sequence of the OS filter.
Another function can be formulated as given in [6] as follows

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W(x) = $r\binom{n}{r}F_X^{r-1}(x)\left(1-F_X(x)\right)^{n-r}$--- Equation 5

By substituting u= $F_X(x)$, for simplicity, and x= $F_X^{-1}(u)$, we get a new function defined as sort function as given [6] below

$w_{r:n} = r\binom{n}{r}u^{r-1}(1-u)^{n-r}$--- Equation 6

The output of the OS filter is given as the expected value of the integral of this sort function and the inverse distribution function as given [6] below.

E[$X_{r:n}$] = $\int_0^1 F_X^{-1}(u)\, w_{r:n}$ du --- Equation 7

The distribution functions of the target and that of target plus clutter will be plotted. The order statistic filters will focus on the quantile estimates, where a significant difference exists. For a given *n* samples of the signal, the OS filter has the freedom to generate upto*n* quantiles. Increasing the number of quantiles will help to focus on the particular regions of the distributions more accurately.

Earlier, two of the popularly usedpost detection processors are the n-pulse integrator and binary integrator. n-pulse integrator is the oldest technique in post processing. It averages the return signals of the multiple transmitted signals to reduce the noise. Binary integrator, also called the double threshold detector, applies two thresholds, one at the input and another at its output. It counts the number of times the return signal exceeds a threshold and the number of times the first threshold was exceeded, is compared to another threshold for the decision. The OS filter is equivalent to the binary integrator when a threshold is applied to the output of the OS filter.

The order statistics filter is shown to be a quantile estimator of the input density function that describes a specific point on the probability distribution function. After choosing the quantile, threshold will be calculated by finding the variance of each channel output. This threshold will be compared with outputs from all range cells and flaw can be detected if any range cell value exceeds the threshold.

VI. SIMULATION STUDY

A wide band signal is simulated which is the transmitted ultrasound. The received echo signal is also simulated. The receiver simulation was also done. Then correlation of transmitted and received signal was taken. Frequency spectrum of correlated output was taken using FFT.

Since the target was fixed on a particular range cell, it was seen that the peak values occur at that particular range cell in the spectrum of the correlated output signal. In the other range cells, reverberation and noise were more prominent. Spectrum was split into 10 bands using 10 Gaussian filters. IFFT of the outputs from these sub bands was taken. It can be seen that high SNR is obtained in the second range cell where the target is fixed, when compared to the other range cells.The output of these 10 filters are analyzed and should be applied to the post processing block, which mainly consists of Order Statistic Filters and thresholding, to obtain an optimized output.

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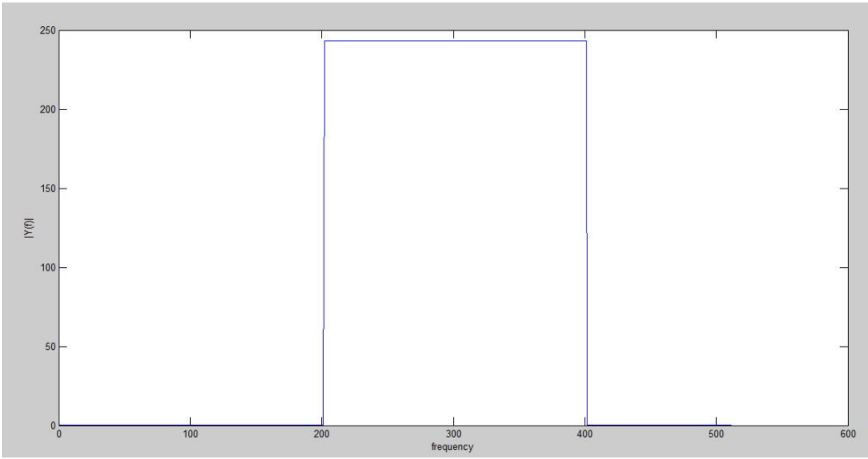

Fig.4 Transmitted wide band spectrum

The above figure shows the spectrum of the wide band signal used for transmitting. The frequencies selected are from 200 to 400 Hz. For ultrasonic testing,frequency of 500MHz will also be used. The frequencies are scaled to 1000 times for computational simplicity.

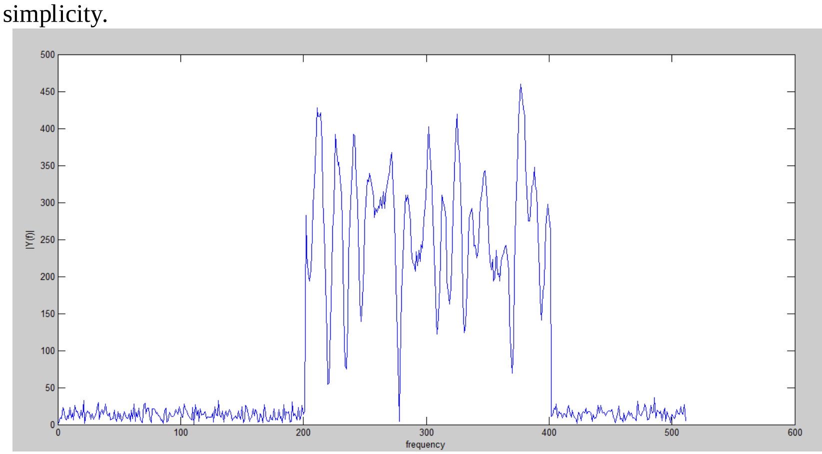

Fig.5 Received signal spectrum

The above figure shows the spectrum of the received signal. It is a combination of the transmitted signal, noise and reverberation. Reverberation is due to the presence of the scatterers or microstructures within the material. It is assumed that the signal from the target is the transmitted signal itself. So the received signal is the combination of the transmitted signal, reverberation and white Gaussian noise.

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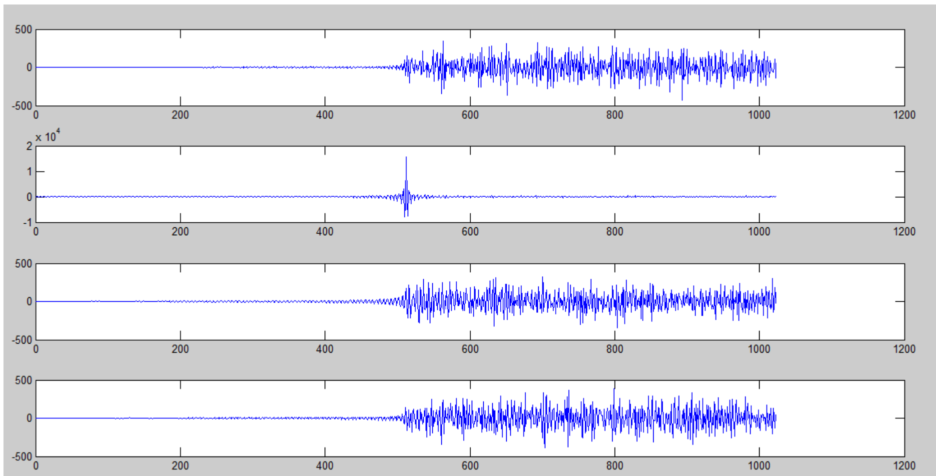

Fig 6 Correlated output

The above figure shows the correlated output for the four range cells. Since the target is fixed on the second range cell, peak value occurs in the second sub-plot.

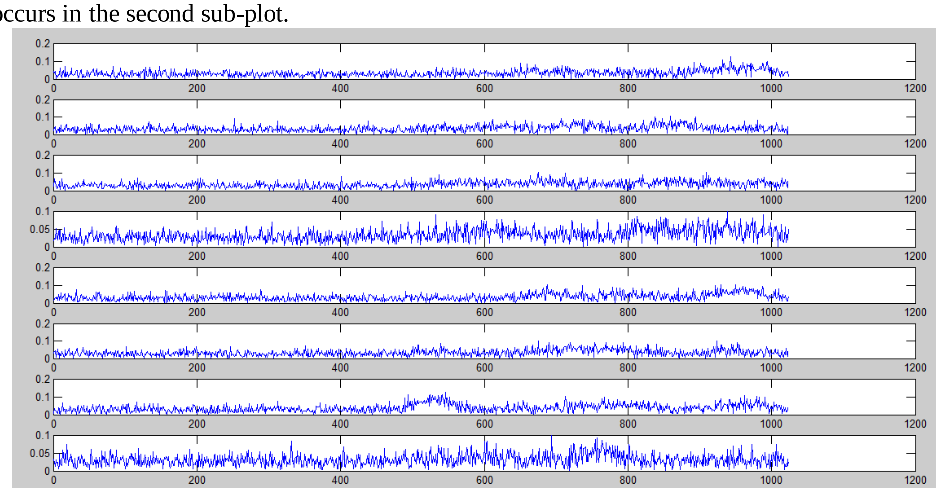

Fig7IFFT output of the first range cell

The above figure shows the IFFT output of the first range cell in which there is notarget(flaw) and the input SNR is15db .Similar graphs are obtained for the other range cells where there is no target.

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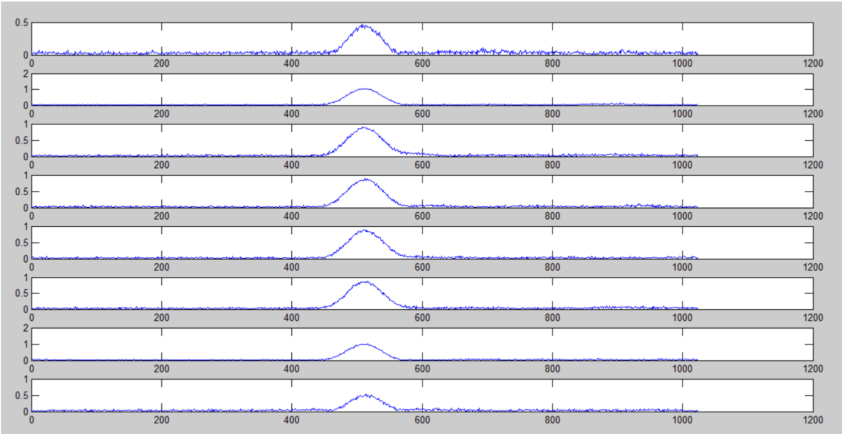

Fig8IFFT output of the second range cell

The above figure shows the splitting of the second range cell in which there is target and with input SNR of 15db. Since there is target, output SNR ishigher as compared to the range cell where there is no target.

VII.CONCLUSION

From the simulations done, it has been observed that SNR of the range cell where target is fixed, remain almost constant while SNR values at the other range cells keep fluctuating, due to reverberation and noise. Also due to spectral splitting improved output SNRs were obtained for different input SNRs as shown below. The approximate values are shown in Table 1.

TABLE 1 OBSERVATION WITH DIFFERENT SNRs

Input SNR	Output SNR First Cell	Output SNR Second Cell (with target)	Output SNR Third Cell	Output SNR Fourth Cell
0db	-0.2 db	1.24db	-1db	-1.45db
5db	-1.2db	9db	0.6db	1.2db
10db	-0.27db	17db	0.27db	1.3db
15db	-0.87db	28db	2db	1.88db

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