NON DESTRUCTIVE TESTING OF MATERIALS BY BICEPSTRUM ANALYSIS OF ULTRASONIC SIGNALS

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ABSTRACT

Non destructive testing of materials is an open field for signal processing applications. Bicepstrum analysis of the signal can be employed and pulse reconstruction achieved. Some simulations will be done in order to check the accuracy of this technique. The general applicability will be illustrated with ultrasonic signals coming from two different cement paste blocks.

1. INTRODUCTION

The analysis of the signal obtained on an ultrasonic transducer when it travels through a dispersive material can give us a lot of information about the inside of the material. The modeling of this problem is a difficult task due to the effect of selective attenuation of frequencies what leads to pulse distortion. A signal processing model of a time varying pulse through a system that models the reflectivity is a good alternative for the modeling of this kind of situations (see figure 1). There are many different alternatives to extract the pulse shape at a given depth (slow distortion of the pulse is assumed) among them we have selected bicepstrum techniques. We will use this technique to compare between two different cement paste specimens.

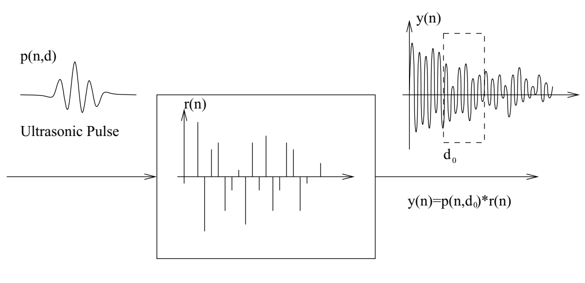

Figure 1: A simple classification scheme based on higher order statistics

The next section will give a brief resume of the theoretical bicepstrum calculation. In section 3 some simulations will be done in order to know the error when using bicepstrum analysis. Finally in section 4 we illustrate this technique with with some real measures in cement paste specimens.

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2. PULSE EXTRACTION THROUGH BICEPSTRUM ESTIMATION

Let $p(n,d)$ be the sampled ultrasonic pulse that would be recorded at the location of the transducer from an isolated scatterer located at depth d. We are going to work at a certain depth d_0 in the material, so that the pulse that we are trying to extract will be $p(n,d_0) = p_{d_0}(n)$. The hypothesis that pulse does not change with depth, d for scatterers located in a certain interval around d_0 is going to be assumed through all our work (slow depth varying pulse hypothesis).

Let $P_{d_0}(z)$ be the transfer function of the ultrasonic pulse $p_{d_0}(n)$ written as

$$P_{d_0}(z) = Az^{-r}I(z^{-1})O(z) \tag{1}$$

where A is a constant, r is an integer, $I(z^{-1})$ is the minimum phase component and $O(z)$ is the maximum phase component.

If we assume that the LTI that models the reflectivity of the material has an impulse response $r(n)$ that can be assumed to be a zero-mean non-Gaussian white i.i.d process with skewness γ_3^r (figure 1), then the output bispectrum $C_3^y(z_1,z_2)$ exist and is given by [1],

$$C_3^y(z_1,z_2) = \gamma_3^r P_{d0}(z_1)P_{d0}(z_2)P_{d0}(z_1^{-1}\cdot z_2^{-1}) \tag{2}$$

$C_3^y(z_1,z_2)$ is the Z-Transform of $C_3^y(\tau_1,\tau_2)$.

According to [2] the bicepstrum is the inverse 2-D Z transform of the log bicepstrum $C_3^y(z_1,z_2)$,

$$b_y(m,n) = Z_2^{-1}\{ln[C_3^y(z_1,z_2)]\} \tag{3}$$

An easy method for computing the cepstral coefficients is based on two-dimensional FFT operations (see figure 2 for an example of how bicepstrum looks like)):

$$m\cdot b_y(m,n) = F_2^{-1}\{\frac{F_2[m\cdot m_3^y(m,n)]}{F_2[m_3^y(m,n)]}\} \tag{4}$$

where $m_3^y(m,n)$ is the third order moment of y, $F_2[\cdot]$ is the 2-D Fourier Transform and $F_2^{-1}[\cdot]$ its inverse. The size of the region of support of $F_2[\cdot]$ or $F_2^{-1}[\cdot]$ should be chosen greater or equal to $2\cdot max[p,q]$ where,

$$\begin{aligned} p &= ln(c)/ln(a) \\ q &= ln(c)/ln(b) \end{aligned} \tag{5}$$

a and c are the maximum (in modulus) cero and pole of the minimum phase component. b is the maximum (in modulus) cero of the maximum phase component.

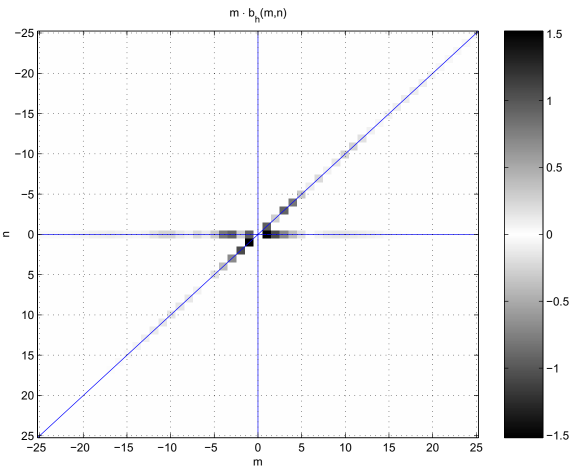

Figure 2: An example of obtaining bicepstrum through equation (4). Note that bicepstrum on the vertical straight line does not appear due to the product $\cdot m$.

It is accomplished that the bicepstrum is the complex cepstrum of $y(t)$ along three straight lines, and zero elsewhere.

$$c_y(m) = b_y(m,0) = b_y(0,m) = b_y(-m,-m), m \neq 0 \quad (6)$$

all of this can be used to recover the complex cepstrum as well as cepstral parameters which contain minimum and maximum phase information. The pulse shape, without minimum phase assumption, can then be extracted. The only ambiguity that can not be recovered using this method deals with an scale factor. Complex cepstrum at the origin $c_h(m) = ln(|A|), m = 0$ can not be recovered due to the method of computing bicepstrum on equation (4).

3. SIMULATIONS

The following simulation will show how with a small number of points pretty good reconstruction of the ultrasonic pulse can be achieved. The reflectivity is going to be modeled with zero-mean exponential white i.i.d noise with unit skewness. The selected region for pulse extraction is going to be of 256 points. The pulse convolved with the reflectivity is modeled as the impulse response of a nonminimum phase system $P_{d_0}(z)$, and only 30 points of this signal will be extracted.

$$P_{d_0}(z) = \frac{(z-0.9)\cdot(1-1.52\cdot z+0.617\cdot z^2)}{(z-0.86)\cdot(z^2-z+0.61)} \quad (7)$$

According to equation (4) and (6) complex cepstrum can be obtained from horizontal and diagonal straight lines. Detailed analysis of estimators coming from horizontal and diagonal lines show that variance depends on the algorithm used to estimate and from the pulse that we are trying to estimate itself. There is no a priori knowledge of which one will give us the lowest variance estimates, simulations for different reflectivity models have been done (see table 1). Using the results of the table 1, we propose the estimation of the $|P_{d_0}(\omega)|$ using the diagonal slice of the bicepstrum. For the estimation of $\angle P_{d_0}(\omega)$ we will use the averaged estimates from horizontal and diagonal slices.

Exponential reflectivity		
Estimator (slice)	Max. modulus std	Max.phase std
Horizontal	1.34	1.81
Diagonal	0.46	1.86
Horiz. + Diag.	0.77	1.02
Rayleigh reflectivity		
Estimator (slice)	Max. modulus std	Max.phase std
Horizontal	1.74	1.42
Diagonal	0.55	1.68
Horiz. + Diag.	0.91	1.00

Table 1: Maximum standard deviation through estimates from the three bicepstrum slices (Standard deviation obtained through 100 Monte Carlo runs)

As an example figures (3) and (4) show comparison between theoretical pulse and recovered pulse using the proposed bicepstrum method. Figures also show an indication of how variance should look like on the worst case.

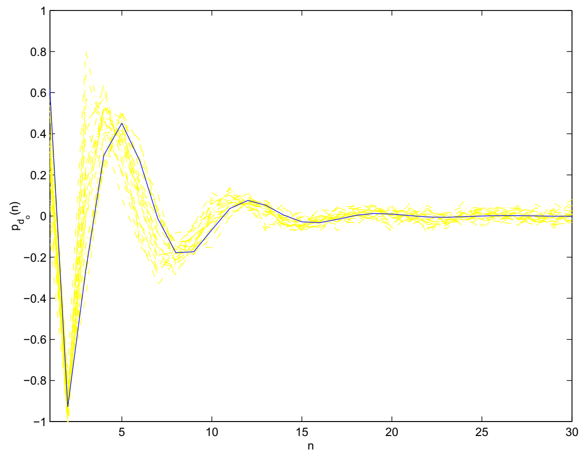

Figure 3: Recovered pulse $p_{d_0}(n)$. Theoretic solid line, dashed line estimated through 25 Monte Carlo runs

4. AN APPLICATION TO PULSE EXTRACTION ON CEMENT PROBES

We have selected cement paste as material to check the estimation feasibility of ultrasonic pulse at a given depth d_0. Cement paste can be considered as hydrated gel matrix and pore cavities not occupied by gel. There are several types of pores, among them capillary porosity mainly determines the total porosity and also the quality of the cement paste. The porosity of the final material can be controlled by means of the water/cement ratio of the mixture [3, 4]. If an adequate ultrasonic frequency is chosen (λ comparable to pore diameter) the pore structure acts as reflectors resembling the model of figure (1).

Two different cement paste blocks have been chosen first one is made of CEM II-Al 32.5 with a water cement ratio of

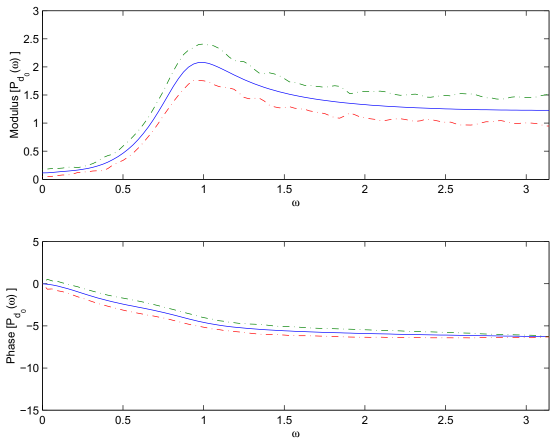

Figure 4: Recovered pulse $P_{d_0}(\omega)$. Theoretic solid line, dashed line maximum/minimum variance values obtained through 25 Monte Carlo runs

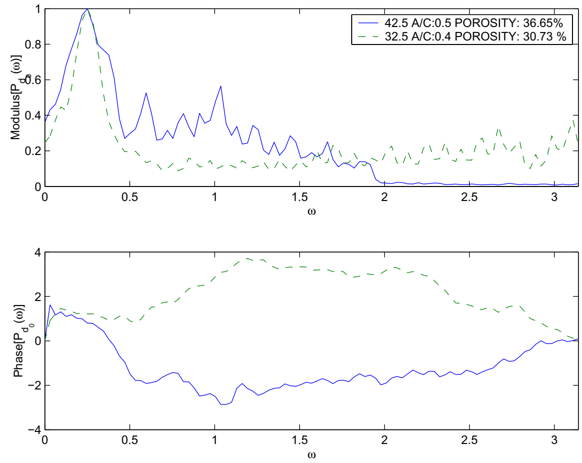

Figure 5: Pulse estimates on two different cement paste blocks at 1600 points depth

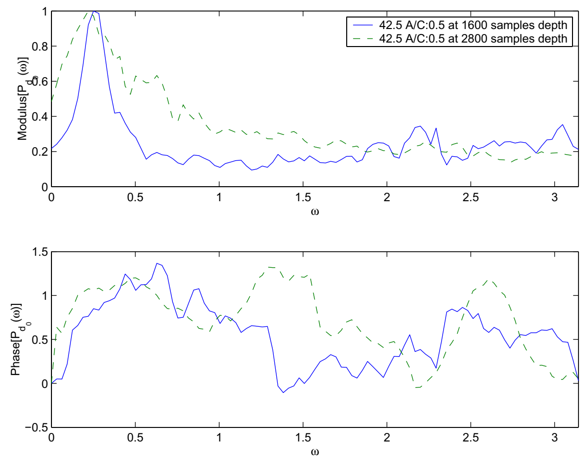

Figure 6: Pulse estimates on a cement block at 1600 points depth and 2800 points depth

0.4. Second one is made of CEM II-Al 42.5 with a water cement ratio of 0.5. Nondestructive measures have been made on these blocks with an ultrasonic PC board IPR-100 (Physical Acoustics) with 400 V of attack voltage and 55 dB in the receiver amplifier. The transducer frequency was chosen to be 10MHz (MSWQC10 transducer from Krautkramer & Branson). Received signal was acquired with the Tektronix 3000 oscilloscope (f_s=250 MSamples/s).

After that, destructive measurements have been made on the cement paste specimens giving porosities of 30.73 % for the 32.5 specimen and 36.65 % for the 42.5 specimen.

Pulse extraction has been made following algorithm described in section 3. Third order moment estimates have been made using method described in [5] (asymptotically unbiased estimator) with records of 256 points. We have averaged 10 of these estimates to obtain the final third order moment estimate. The frequency response has been finally obtained from the relationship $ln[P_{d_0}(\omega)] = F[c_h(n)]$ where $F[.]$ is the 1-D Fourier Transform. Results are plotted in the figure 5 where it can be seen that higher porosity results in a larger bandwidth pulse at the same depth (1600 points). Differences can also be seen in the phase of $P_{d_0}(\omega)$ and used for material classification.

In order to show the distortion of the pulse as it travels through the material we have obtained the pulse at two different depths: 1600 samples and 2800 samples. Figure 6 shows the results for specimen 42.5 (similar results where obtained for the 32.5 specimen). Central frequencies of the two pulses have been also measured giving 9.94 MHz at depth 1600 samples and 8.68 MHz at depth 2800 samples. The figure 6 shows more detailed evolution of the pulse with depth.

5. CONCLUSIONS

We have seen the applicability of bicepstrum for nondestructive testing of materials. With this idea we are capable of obtaining the pulse (without minimum phase assumption) that will be later used for many applications: classification, parameter extraction, etc. With difference to some other techniques recovered phase could also be of interest in classification purposes.

Absolute amplitude of the pulse is lost, so this technique will not be valid if we are concerned on this fact. On the other hand very small a priori knowledge of the pulse is required to obtain quality estimates.

Results obtained seem to fit quite well what we expected from the ultrasonic signals. This indicates that ultrasonic pulse traveling through this kind of material can be modeled this way.

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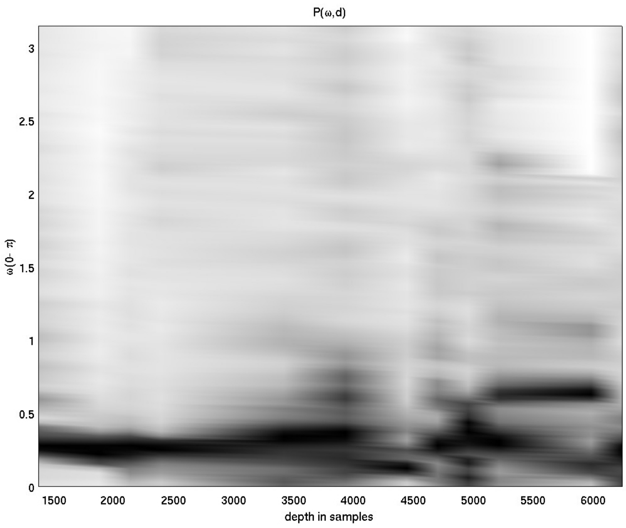

Figure 7: Colormap of pulse estimates with depth. Specimen 42.5 A/C: 0.5

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