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- (71) **Applicant (for all designated States except US):** BAKER HUGHES INCORPORATED [US/US]; P.O. Box 4740, Houston, TX 77210-4740 (US).
- (72) **Inventor; and**
- (75) **Inventor/Applicant (for US only):** ZHAO, Jinsong [CN/US]; 3929 Gibson, Houston, TX 77007 (US).
- (74) **Agents:** CARSON, Matt, W. et al.; Baker Hughes Incorporated, P.o. Box 4740, Houston, TX 77210-4740 (US).

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(54) **Title:** EMAT ACOUSTIC SIGNAL MEASUREMENT USING MODULATED GAUSSIAN WAVELET AND HILBERT DEMODULATION

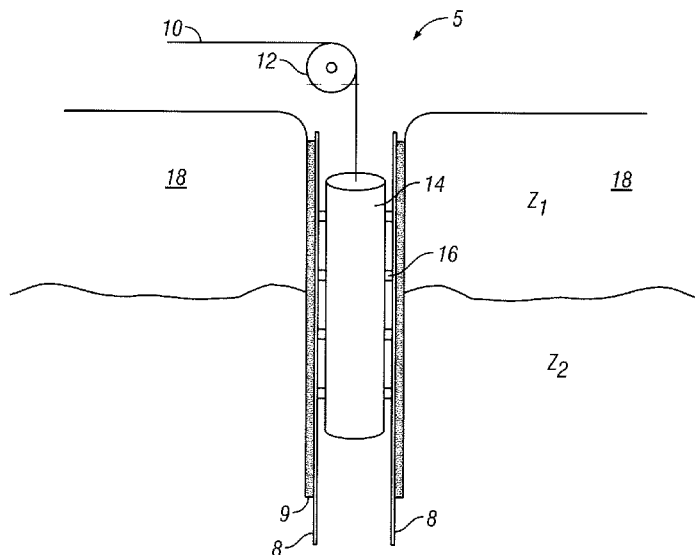


Figure 1
(Prior Art)

(57) **Abstract:** Casing signals generated by an EMAT in a borehole are processed using one or more band-limited Gaussian filters. By using the Hubert transform, an envelope of the filtered signals is determined and amplitudes and arrival times of individual arrivals are estimated. These can be used to estimate casing and cement properties.

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EMAT ACOUSTIC SIGNAL MEASUREMENT USING MODULATED GAUSSIAN WAVELET AND HILBERT DEMODULATION

Inventor: Jinsong Zhao

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FIELD OF THE DISCLOSURE

[0001] The disclosure relates generally to the field of the evaluation of wellbore casing. More specifically the present disclosure relates to a method and apparatus to provide for the analysis of casing within a wellbore environment by producing
0 and recording characteristics of waveforms traversing the casing and cement.

BACKGROUND OF THE DISCLOSURE

[0002] As illustrated in **Figure 1** wellbores typically comprise casing **8** set within the wellbore **5**, where the casing **8** is bonded to the wellbore by adding cement **9** within the annulus formed between the outer diameter of the casing **8** and the
15 inner diameter of the wellbore **5**. The cement bond not only adheres to the casing **8** within the wellbore **5**, but also serves to isolate adjacent zones (e.g. Z_1 and Z_2) within an earth formation **18**. Isolating adjacent zones can be important when one of the zones contains oil or gas and the other zone includes a non-hydrocarbon fluid such as water. Should the cement **9** surrounding the casing **8** be defective
20 and fail to provide isolation of the adjacent zones, water or other undesirable fluid can migrate into the hydrocarbon producing zone thus diluting or contaminating the hydrocarbons within the producing zone, and increasing production costs, delaying production or inhibiting resource recovery.

[0003] To detect possible defective cement bonds, downhole tools **14** have been
25 developed for analyzing the integrity of the cement **9** bonding the casing **8** to the wellbore **5**. These downhole tools **14** are lowered into the wellbore **5** by wireline **10** in combination with a pulley **12** and typically include transducers **16** disposed on their outer surface formed to be acoustically coupled to the fluid in the borehole. These transducers **16** are generally capable of emitting acoustic waves
30 into the casing **8** and recording the amplitude of the acoustic waves as they travel, or propagate, across the casing **8**. Characteristics of the cement bond, such as its efficacy, integrity and adherence to the casing, can be determined by analyzing

characteristics of the acoustic wave such as attenuation. Typically the transducers
16 are piezoelectric devices having a piezoelectric crystal that converts electrical
energy into mechanical vibrations or oscillations transmitting acoustic wave to the
casing 8. Piezoelectric devices typically couple to a casing 8 through a coupling
5 medium found in the wellbore. Coupling mediums include liquids that are
typically found in wellbores. When coupling mediums are present between the
piezoelectric device and the casing 8, they can communicate the mechanical
vibrations from the piezoelectric device to the casing 8. However, lower density
~~fluids such as gas or air and high viscosity fluids such as some drilling mud may~~
10 not provide adequate coupling between a piezoelectric device and the casing 8.
Furthermore, the presence of sludge, scale, or other like matter on the inner
circumference of the casing 8 can detrimentally affect the efficacy of a bond log
acquired with a piezoelectric device. Thus for piezoelectric devices to provide
meaningful bond log results, they must cleanly contact the inner surface of the
15 casing 8 or be employed in wellbores, or wellbore zones, having liquid within the
casing 8. Another drawback faced when employing piezoelectric devices for use
in bond logging operations involves the limitation of variant waveforms produced
by these devices. Fluids required to couple the wave from the transducer to the
casing only conduct compressional waves, thus limiting the wave types that can
20 be induced in or received from the casing. A great deal of information is
derivable from variant acoustical waveforms that could be used in evaluating
casing, casing bonds, and possibly even conditions in the formation 18.
Therefore, there exists a need to conduct bond logging operations without the
presence of a particular couplant. A need exists for a bond logging device capable
25 of emitting and propagating into wellbore casing numerous types of waveforms,
and recording the waveforms.

[0004] U.S. Patent No. 7,311,143 to *Engels et al.*, having the same assignee as the
present disclosure and the contents of which are incorporated herein by reference,
discloses a method and apparatus for inducing and measuring acoustic waves,
30 including shear waves, within a wellbore casing to facilitate analysis of wellbore
casing, cement and formation bonding. An acoustic transducer is provided that is

magnetically coupled to the wellbore casing and is comprised of a magnet combined with a coil, where the coil is attached to an electrical current. The acoustic transducer is capable of producing and receiving various waveforms, including compressional waves, shear waves, Rayleigh waves, and Lamb waves.

5 The transducer remains coupled to the wellbore casing as the tool traverses portions of the casing. An important aspect of the method of *Engels* is the ability to identify different modes of propagation of acoustic signals within the casing. The amplitude and times of arrival of the different signals is indicative of ~~properties of the casing. The present disclosure provides an improved method for~~
10 the estimation of arrival times and amplitudes of these different modes. For the purposes of the present disclosure, the individual arrivals may be referred to as “events.”

SUMMARY OF THE DISCLOSURE

15 [0005] One embodiment of the disclosure is a method of characterizing a casing installed in a borehole in an earth formation. The method includes activating a transducer at at least one azimuthal orientation in the borehole and generating an acoustic pulse; receiving a signal comprising a plurality of events resulting from the generation of the acoustic pulse; bandpassing the received signal using a modulated Gaussian filter and providing a bandpassed signal; estimating an
20 envelope of the bandpassed signal; and estimating from the envelope of the bandpassed signal an arrival time of each of the plurality of events, the arrival times being characteristic of a property of the casing, and/or a cement in an annulus between the casing and the formation.

25 [0006] Another embodiment of the disclosure is an apparatus for characterizing a casing installed in a borehole in an earth formation. The apparatus includes a transducer configured to generate an acoustic pulse at at least one azimuthal orientation in the borehole; a receiver configured to receive a signal comprising a plurality of events resulting from the generation of the acoustic pulse; and a processor configured to: bandpass the received signal using a modulated Gaussian
30 filter and provide a bandpassed signal; estimate an envelope of the bandpassed signal; and estimate from the envelope of the received signal an arrival time of

each of the plurality of events, the arrival times being characteristic of a property of at least one of: (i) the casing, and (ii) a cement in an annulus between the casing and the formation.

[0007] Another embodiment of the disclosure is a computer-readable medium
5 accessible to a processor. The computer-readable medium including instructions which enable the processor to characterize a property of a casing in a borehole in an earth formation using a signal comprising a plurality of events resulting from generation of an acoustic pulse by a transducer in the borehole, the instructions
including bandpassing the signal using a modulated Gaussian function, estimating
10 an envelope of the bandpassed signal and estimating from the envelope an arrival time of each of the plurality of events.

BRIEF DESCRIPTION OF THE FIGURES

[0008] The present disclosure and its advantages will be better understood by referring to the following detailed description and the attached drawings in which:

15 **Figure 1** depicts a partial cross section of prior art downhole cement bond log tool disposed within a wellbore;

Figures 2A–2B schematically illustrate a magnetic coupling transmitter disposed to couple to a section of casing;

Figure 3 shows an exemplary EMAT tool disposed within a wellbore;

20 **Figures 4(a), 4(b)** show exemplary signals recorded using six transducers;

Figure 5 shows exemplary signals of SH0 and SH1 modes recorded at a transducer;

Figures 6a, 6b show examples of the Gaussian operator in the time domain and the frequency domain;

25 **Figures 7(a), 7(b)** show a modulated Gaussian function in (a) the time domain (a) and (b) the frequency domain;

Figures 8(a), 8(b) show an exemplary signal and noise (a) in the time domain and in the frequency domain (b);

30 **Figures 9(a), 9(b)** show an exemplary filtered signal and noise (a) in the time domain and in the frequency domain (b);

Figures 10(a), 10(b) show a demodulated signal envelope and peak of the envelope;

Figures 11(a), 11(b) show exemplary bench data and a detailed window thereof;

5 **Figure 12(a)** shows exemplary operators for the SH0 and SH1 wavelets; **Figure 12(b)** shows the spectra of the SH0 and SH1 wavelets of **Figure 12(a)** and the input signal;

Figures 13(a), 13(b) show reconstructed wavelets recovered from the input signal;

10 **Figure 14(a)** shows the reconstructed spectra using the SH0 and SH1 wavelets along with the data of **Figure 11(b)**;

Figure 14(b) shows the reconstructed data signal using the SH0 and SH1 wavelets;

15 **Figure 15** shows the envelope of the signal of **Figure 11(a)** recovered using the SH0 and SH1 wavelets; and

Figure 16 is a flow chart illustrating some of the steps of the present disclosure.

DETAILED DESCRIPTION OF THE DISCLOSURE

20 [0009] As illustrated in **Figure 2A**, a magnetically coupled transducer **20** is positioned at any desired attitude proximate to a section of casing **8**. For the purposes of clarity, only a portion of the length and diameter of a section of casing **8** is illustrated and the magnetically coupled transducer **20** is shown schematically in both **Figure 2A** and **Figure 2B**. The magnetically coupled transducer **20** may be positioned within the inner circumference of the tubular casing **8**, but the
25 magnetically coupled transducer **20** can also be positioned in other areas.

[0010] For any particular transducer **20**, more than one magnet (of any type for example permanent, electro-magnetic, etc.) may be combined within a unit; such a configuration enables inducing various waveforms and facilitating measurement and acquisition of several waveforms. A transducer **20** capable of transmitting or
30 receiving waveforms in orthogonal directions is schematically illustrated in **Figure 2B**. While a schematic magnet **22** with orthogonal magnetic fields is

illustrated, a single-field relatively large magnet with multiple smaller coils **24** (which coils may be disposed orthogonally) may be employed to form versatile transducers.

[0011] In embodiments provided by the present disclosure that are illustrated schematically in **Figure 2A** and **2B**, the magnetically coupled transducer **20** is comprised of a magnet **22** and a coil **24**, where the coil **24** is positioned between the magnet **22** and the inner circumference of the casing **8**. An electrical current source (not shown) is connectable to the coil **24** capable of providing electrical current to the coil **24**. The magnet **22**, may be one or more permanent magnets in various orientations or can also be an electro-magnet, energized by either direct or alternating current. **Figure 2B** schematically illustrates orthogonal magnetic and coil representations. One or more magnets or coils may be disposed within a downhole tool to affect desired coupling and/or desired wave forms such as the direct inducing of shear waves into casing **8**. While the coil is illustrated as disposed between the magnet and the casing, the coil may be otherwise disposed adjacent to the magnet.

[0012] The coil **24** may be energized when the magnetically coupled transducer **20** is proximate to the casing **8** to produce acoustic waves within the material of the casing **8**. For example the coil may be energized with a modulated electrical current. Thus the magnetically coupled transducer **20** operates as an acoustic transmitter.

[0013] The magnetically coupled transducer **20** can also operate as a receiver capable of receiving waves that traversed the casing and cement. The magnetically coupled transducer **20** may be referred to as an acoustic device. As such, the acoustic devices of the present disclosure function as acoustic transmitters or as acoustic receivers, or as both.

[0014] An exemplary embodiment of the tool as illustrated in **Figure 3** provides a sonde **30** shown having acoustic devices disposed on its outer surface. The acoustic devices comprise a series of acoustic transducers, both transmitters **26** and receivers **28**, where the distance between each adjacent acoustic device on the same row may be substantially the same. With regard to the configuration of

acoustic transmitters **26** and acoustic receivers **28** shown in **Figure 3**, while the rows **34** radially circumscribing the sonde **30** can comprise any number of acoustic devices (i.e. transmitters **26** or receivers **28**), in one embodiment, each row **34** comprise five or more of these acoustic devices (the preference for five or more devices is for devices with the transmitters and receivers radially arranged around the circumference). The acoustic transmitters **26** may be magnetically coupled transducers **20** of the type of **Figure 2A** and **2B** comprising a magnet **22** and a coil **24**. Optionally, the acoustic transmitters **26** can comprise ~~electromagnetic acoustic transducers.~~

[0015] Referring now again to the configuration of the acoustic transmitters **26** and acoustic receivers **28** of **Figure 3**, the acoustic transducers comprising transmitters **26** and receivers **28** can be arranged in at least two rows where each row comprises primarily acoustic transmitters **26** and a next adjacent row comprises primarily acoustic receivers **28**. Optionally, as shown in **Figure 3**, the acoustic devices within adjacent rows in this arrangement are aligned in a straight line along the length of the sonde **30**.

[0016] While only two circumferential rows **34** of acoustic devices are shown in **Figure 3**, variations and placement of transducers and arrangements in rows can be included depending on the capacity and application of the sonde **30**. Another arrangement is to have one row of acoustic transducers **26** followed by two circumferential rows of acoustic receivers **28** followed by another row of acoustic transducers **26**. As is known in the art, advantages of this particular arrangement include the ability to make a self-correcting acoustic measurement. Attenuation measurements are made in two directions using arrangements of two transmitters and two receivers for acquisition of acoustic waveforms. The attenuation measurements may be combined to derive compensated values that do not depend on receiver sensitivities or transmitter power.

[0017] **Figure 4(a)** shows a cross-section of the sonde in which six transducers **D1**, **D2**, **D3**, **D4**, **D5** and **D6** are shown around the circumference of the sonde. The six transducers define six sectors **S1**, **S2**, **S3**, **S4**, **S5** and **S6**. Shown in **Figure 4(a)** are exemplary signals **411** and **413**. The signal **411** depicts a signal at

transducer **D2** resulting from the activation of transducer **D1**, while the signal **413** shows the signal at transducer **D3** resulting from the activation of transducer **D1**. Similarly, **415** shows the signal at **D2** resulting from the activation of transducer **D4** and **417** shows the signal at **D2** resulting from the activation of transducer **D4**.

5 **[0018]** We denote by A_{ij} the signal at transducer j resulting from the activation of transducer i . Then the attenuation of the signals in sector **S2** can be represented by

$$A_{S2} = 10 \log_{10} \frac{\left(\frac{A_{12} A_{43}}{A_{13} A_{42}} \right)}{\Delta} \quad (1).$$

10 **[0019]** Due to the bandwidth limitation, the downhole tool has to demodulate the received signals to estimate their amplitudes (as well as arrival times). Ideally, the received signals are expected as shown in the curves **411, 413, 415, 417** in **Figures 4(a), 4(b)**. A signal-to-noise ratio (SNR) of 60dB provides for good estimation of arrival times and amplitudes. However, in reality, the SNR of the

15 received signals is only around 30dB to 40dB. As discussed in U.S. Patent Application Ser. No. 11/358,172 (U.S. 2007/0206439) of *Barolak et al.*, having the same assignee as the present disclosure and the contents of which are incorporated herein by reference, shear waves and Lamb waves may be used to determine the integrity of a cement bond. In addition, a problem arises from the

20 fact that the SH0 and SH1 may be excited simultaneously due to the wide spectral of the stimulus signal from the transducers.

[0020] For the purposes of illustrating the method of the present disclosure, reference is first made to **Figure 5** which shows exemplary signals recorded on a test bench. Two signals recorded under different casing conditions are denoted by

25 **501** and **503**. The signal from 0 to about 130 is ringing (from the system). The signal from 130 to about 260 is SH0 with (the center frequency is about 200KHz), while the signal from 180 to 420 is SH1 with the center frequency is about 280KHz. As can be seen, the SH0 and the SH1 signals are overlapped each other. In **501**, the ringing also affects the SH0. The method used in the present disclosure

is to separate the SH0 from SH1. It is to be noted that the curve **501** has a strong SH0 mode while the curve **503** has strong SH1 mode. Of particular interest are the times of arrival of the different modes that may be referred to as “events.”

[0021] An effective way to estimate the time of arrival of an event is to first
 5 estimate the envelope of a wavelet. In one embodiment of the disclosure, this is done by using the Hilbert transform. An acoustic signal $f(t)$ such as that in **Figure 4(a)** can be expressed in terms of a time-dependent amplitude $A(t)$ and a time-dependent phase $\theta(t)$ as:

$$f(t) = A(t) \cos \theta(t) \quad (2)$$

10 Its quadrature trace $f^*(t)$ then is:

$$f^*(t) = A(t) \sin \theta(t) \quad (3),$$

and the complex trace $F(t)$ is:

$$F(t) = f(t) + jf^*(t) = A(t)e^{j\theta(t)} \quad (4).$$

If $f(t)$ and $f^*(t)$ are known, one can solve for $A(t)$ as

$$15 \quad A(t) = \left[f^2(t) + f^{*2}(t) \right]^{1/2} = |F(t)| \quad (5)$$

as the envelope of the signal $f(t)$.

[0022] One way to determine the quadrature trace $f^*(t)$ is by use of the Hilbert transform:

$$f^*(\tau) = p.v. \int_{-\infty}^{\infty} \frac{f(t)}{\tau - t} dt \quad (6),$$

20 where *p.v.* represents the principal value. The Hilbert transform needs a band-limited input signal and is sensitive to wide-band noise. Consequently, before applying the Hilbert transform, a band-pass filter is applied. In the present method, a Gaussian filter is used as the band-pass filter.

[0023] **Figures 6(a)**, **6(b)** show representations of two different Gaussian filters in
 25 the time domain (**Figure 6(a)**) and in the frequency domain (**Figure 6(b)**). The Gaussian filter in the time domain is given by

$$g(t) = e^{-\pi \left(\frac{t}{\tau} \right)^2} \quad (7).$$

Its Fourier transform is given by

$$G(f) = \tau e^{-\pi(\tau f)^2} \quad (8).$$

An advantage of the Gaussian filter that can be seen in **Figures 6(a), 6(b)** is that there are no ripples in either the time domain or in the frequency domain. By choosing τ , it is possible to capture information carried by the signal.

- 5 **[0024]** If the Gaussian function is modulated with a carrier frequency f_c in the time domain, the result is a signal

$$g_M(\tau, f_c, t) = g(\tau, t) \cos(2\pi f_c t) \quad (9),$$

and a frequency domain realization:

$$G_M(\tau, f_c, f) = G(\tau, f) \otimes \delta(f - f_c) \quad (10),$$

- 10 where \otimes represents a convolution and δ is the Kronecker delta function.

Therefore, the $g_M(\tau, t)$ looks like wavelet operator. The localizability (the information time span in time domain and its related frequency bandwidth) is determined by τ and f_c . **Figure 7(a)** shown an example of $g_M(\tau, f_c, t)$ and **Figure 7(b)** shows an example of $G_M(t, f_c, f)$.

- 15 **[0025]** In the example above, f_c equals to 1Hz. The wavelet operator is shown in the time domain and its amplitude spectral response is shown in the frequency domain. From the standpoint of implementation, it is desirable to select the attenuation and bandwidth to control the wavelet operator behaviors (say, -6dB in power with a certain nominal bandwidth NBW) instead of selecting τ . In the
 20 example above, the bandwidth is from $-0.2 f_c$ to $+0.2 f_c$ ($\text{NBW}_{-6\text{dB}} = 40\%$).
 From **eqn. (7)** we have

$$g(t) = e^{-k * t^2}$$

(11)

25

If we define NBW as

$$\mu = \frac{\Delta f}{f_c}$$

(12)

and attenuation factor, α in dB, we have

5

$$k = \frac{5 (\pi \mu f_c)^2}{\alpha * \ln 10}$$

(13)

It is thus possible to choose α and μ to control the spectrum of the wavelet
operator $g_M(\alpha, \mu, f_c, t)$.

10

[0026] The wavelet operator is used to reconstruct the acquired signal with
additive white noise by a convolution operation. The acquired signal may be
denoted by

15

$$x_c(t) = x(t) + n(t)$$

(14)

where, $x(t)$ is the acoustic signal and $n(t)$ is white noise. The convolution
operation is

20

$$y(t) = x_c(t) \otimes g_M(\alpha, \mu, f_c, t)$$

(15)

25 In theory, $g_M(\alpha, \mu, f_c, t)$ is a band-pass filter (BPF). It can attenuate the noise
outside of the pass-band. **Figure 8(a)** shows a signal **801** and the additive white

noise **805** at an SNR of about 0dB while **Figure 8(b)** shows the signal **803** in the frequency domain and the additive white noise **807**. **901** and **905** in **Figure 9(a)** show the filtered signal and noise respectively in the time domain, while **903** and **905** in **Figure 9(b)** show the filtered signal and noise in the frequency domain.

5 **[0027]** The amplitude of the carrier signal is, from **eqn. (5)**, given by:

$$A_{f_c} = \max [A(t)] \Big|_{t=t_c} \quad (16),$$

where t_c is the location of the peak point of $A(t)$. The demodulated envelope curve and the peak detected value are shown by **1001** in **Figure 10(a)** and **1003** in **Figure 10(b)**.

10 **[0028]** The principles described above are next applied to acquired data in a bench test. Shown in **Figure 11(a)** are two exemplary signals **1101**, **1103**. The signals in **Figure 11(a)** include multiple arrivals of SH0 and SH1. A window of the signals in **Figure 11(a)** is shown in detail in **Figure 11(b)** by **1151** and **1153**. In **Figure 11(b)**, only the first arrivals are shown,, and correspond to the signals **501**,
 15 **503** I **Figure 5**. The data includes SH0 arrivals (at ≈ 180 kHz) and SH1 arrivals (at ≈ 280 kHz), and two wavelet operators are used to reconstruct the acquired signal. The operators are shown in the time domain by **1201** and **1203** in **Figure 12(a)**, while **Figure 12(b)** shows the spectra of the wavelet operators **1205** and **1207** along with the spectra of the two input signals. **Figure 13(a)** shows the
 20 original signal **1153** and the recovered SH0 signal **1301** while **Figure 13(b)** shows the original signal **1153** and the recovered SH1 signal **1303**.

[0029] **Figure 14(a)** shows the spectrum **1401** of the data **1153** in **Figure 11(b)**, along with the reconstructed spectrum using the SH0 wavelet **1403**, and the reconstructed spectrum using the SH1 wavelet **1405**. **Figure 14(b)** shows the
 25 envelope **1407** of the reconstructed signal using the SH0 wavelet and the envelope **1409** of the reconstructed signal using the SH1 wavelet.

[0030] **Figure 15** shows the result of processing the signal of **Figure 11(a)** using the SH0 wavelet **1501** and the SH1 wavelet **1503** to estimate the envelope peak amplitudes and times. As can be seen, each of the curves **1501** and **1503** shows
 30 more than one arrival (event). The different events are the result of propagation through the casing in opposite directions, the earliest arrival being associated with

the shortest path from the transmitter to the receiver. The geometry associated with the different arrivals is straightforward, and the analysis of the amplitudes is discussed in *Barolak*.

[0031] The disclosure above has been for a specific wireline tool used analysis of the the casing and quality of cement bond. The principles outlined above may also be used for analysis of reflection signals acquired with wireline or in MWD applications. See, for example, U.S. Patent No. 5,491,668 to *Priest et al.*, and US2007/0005251 of *Chemali et al.*, having the same assignee as the present disclosure the contents of which are incorporated herein by reference. A point of difference between the casing signals discussed in the present disclosure and the reflected signals is that the latter are subject to more attenuation than are the guided casing signals.

[0032] **Figure 16** is a flow chart that summarizes the method of the present disclosure. Starting with a signal **1601**, one or more wavelets are defined **1603**, **1611**. In one embodiment, the wavelets are band-limited Gaussian functions, such as given by **eqn. (9)**. The wavelet characteristics may be defined by the nominal bandwidth and attenuation. The wavelets are applied **1605**, **1613** to the signal, using a suitable windowing function such as a Hanning weighting or a Hamming weighting. A Hilbert transform is used to estimate the envelope of the filtered signals and the peak amplitude and arrival times in the envelope are identified **1607**, **1615**. Based on the estimated arrival times and amplitudes of the signals, the casing and cement bond parameters are estimated **1609**.

[0033] Based on travel-times and amplitudes of the detected arrivals, using known methods, it is then possible to determine one or more of the following: (i) a thickness of the casing, (ii) the acoustic impedance of the cement in proximity to the casing, (iii) a position and size of a void in the cement, and (iv) a position and size of a defect in the casing.

[0034] Implicit in the processing of the data is the use of a computer program implemented on a suitable machine readable medium that enables the processor to perform the control and processing. The machine readable medium may include ROMs, EPROMs, EAROMs, Flash Memories and Optical disks. The determined

formation properties may be recorded on a suitable medium and used for subsequent processing upon retrieval of the BHA. The determined formation properties may further be telemetered uphole for display and analysis.

[0035] The foregoing description is directed to particular embodiments of the present disclosure for the purpose of illustration and explanation. It will be
5 apparent, however, to one skilled in the art that many modifications and changes to the embodiment set forth above are possible without departing from the scope and the spirit of the disclosure. It is intended that the following claims be
interpreted to embrace all such modifications and changes.

CLAIMS

What is claimed is:

- 1 1. A method of characterizing a casing installed in a borehole in an earth
2 formation, the method comprising:
3 activating a transducer at at least one azimuthal orientation in the
4 borehole and generating an acoustic pulse;
5 receiving a signal comprising a plurality of events resulting from
6 ~~the generation of the acoustic pulse;~~
7 bandpassing the received signal using a modulated Gaussian filter
8 and providing a bandpassed signal;
9 estimating an envelope of the bandpassed signal; and
10 estimating from the envelope of the bandpassed signal an arrival
11 time of each of the plurality of events, the arrival times being characteristic
12 of a property of at least one of: (i) the casing, and (ii) a cement in an
13 annulus between the casing and the formation.
- 1 2. The method of claim 1 further comprising estimating from the envelope an
2 amplitude of each of the events.
- 1 3. The method of claim 1 wherein estimating the envelope of the received
2 signal further comprises applying a Hilbert transform.
- 1 4. The method of claim 1 wherein activating the transducer at at least one
2 azimuthal orientation further comprises activating the transducer at a
3 plurality of azimuthal orientations, the method further comprising
4 estimating the property at the plurality of azimuthal orientations.
- 1 5. The method of claim 4 wherein estimating the property at the plurality of
2 azimuthal orientations further comprises estimating an attenuation of a
3 selected mode of propagation characterizing an event.
- 1 6. The method of claim 1 further comprising, using for the transducer, an
2 electromagnetic acoustic transducer.
- 1 7. The method of claim 1 wherein the property is selected from the group
2 consisting of: (i) a thickness of the casing, (ii) an acoustic impedance of

- 3 the cement in proximity to the casing, (iii) a position and size of a void in
4 the cement, and (iv) a position and size of a defect in the casing.
- 1 8. The method of claim 1 further comprising conveying the transducer on a
2 logging tool into the borehole using a wireline.
- 1 9. An apparatus for characterizing a casing installed in a borehole in an earth
2 formation, the apparatus comprising:
- 3 a transducer configured to generate an acoustic pulse at at least one
4 azimuthal orientation in the borehole;
- 5 ~~a receiver configured to receive a signal comprising a plurality of~~
6 events resulting from the generation of the acoustic pulse; and
7 a processor configured to:
- 8 bandpass the received signal using a modulated Gaussian
9 filter and provide a bandpassed signal;
- 10 estimate an envelope of the bandpassed signal; and
11 estimate from the envelope of the received signal an arrival
12 time of each of the plurality of events, the arrival times being
13 characteristic of a property of at least one of: (i) the casing, and (ii)
14 a cement in an annulus between the casing and the formation.
- 1 10. The apparatus of claim 9 wherein the receiver is part of the transducer.
- 1 11. The apparatus of claim 9 wherein the transducer further comprises an
2 electromagnetic acoustic transducer.
- 1 12. The apparatus of claim 9 wherein the processor is further configured to
2 estimate from the envelope an amplitude of each of the events.
- 1 13. The apparatus of claim 9 wherein the processor is further configured to
2 estimate the envelope of the received signal by applying a Hilbert
3 transform.
- 1 14. The apparatus of claim 9 wherein the transducer is further configured to be
2 activated at a plurality of azimuthal orientations and wherein the processor
3 is further configured to estimate the property at a plurality of azimuthal
4 orientations.

- 1 15. The apparatus of claim 12 wherein the processor is further configured to
2 estimate the property at the plurality of azimuthal orientations by
3 estimating an attenuation of a selected mode of propagation characterizing
4 an event.
- 1 16. The apparatus of claim 9 wherein the processor is further configured to
2 estimate a property that is selected from the group consisting of: (i) a
3 thickness of the casing, (ii) an acoustic impedance of the cement in
4 proximity to the casing, (iii) a position and size of a void in the cement,
5 ~~and (iv) a position and size of a defect in the casing.~~
- 1 17. The apparatus of claim 9 further comprising a wireline configured to
2 convey the transducer on a logging tool into the borehole.
- 1 18. A computer-readable medium accessible to a processor, the computer-
2 readable medium including instructions which enable the processor to
3 characterize a property of a casing in a borehole in an earth formation
4 using a signal comprising a plurality of events resulting from generation of
5 an acoustic pulse by a transducer in the borehole, the instructions including
6 bandpassing the signal using a modulated Gaussian function, estimating an
7 envelope of the bandpassed signal and estimating from the envelope an
8 arrival time of each of the plurality of events.
- 1 19. The computer-readable medium of claim 18 further comprising at least one
2 of: (i) a ROM, (ii) an EPROM, (iii) an EAROM, (iv) a flash memory, and
3 (v) an optical disk.

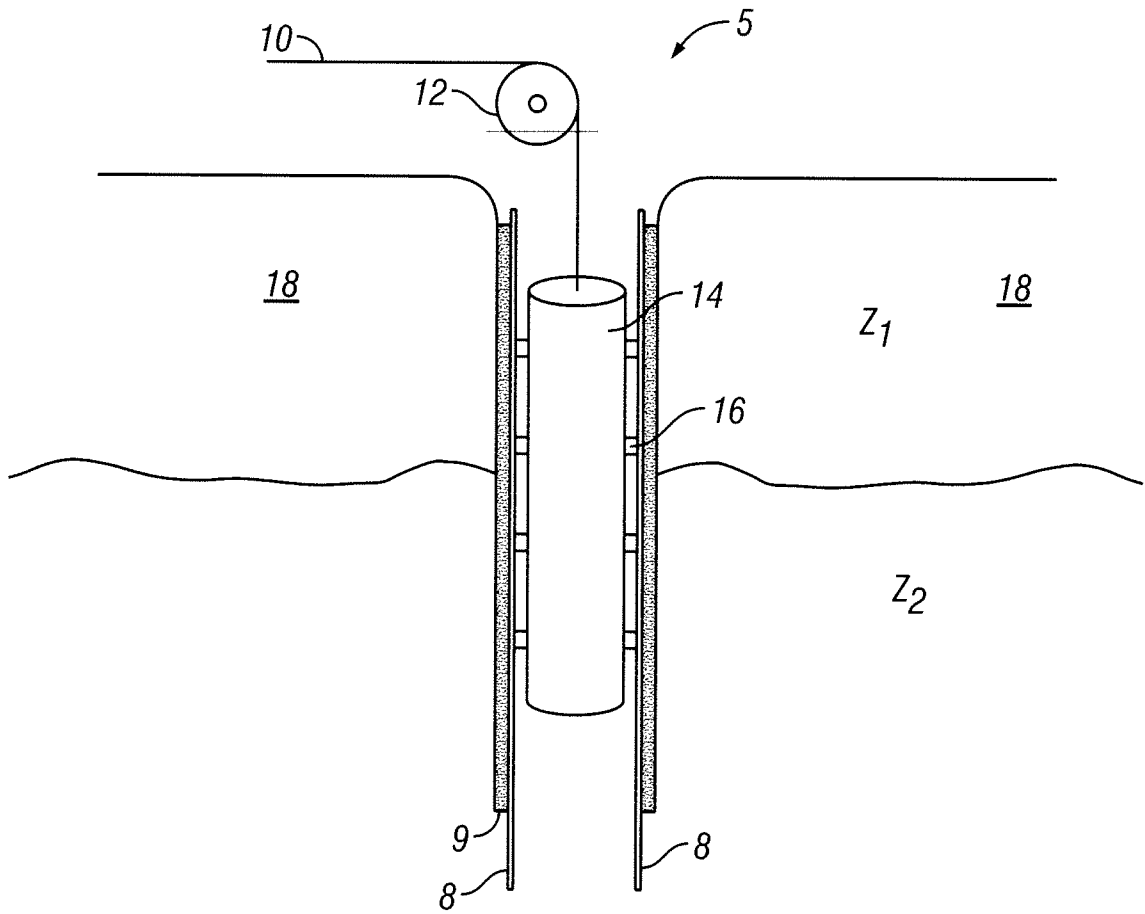


Figure 1
(Prior Art)

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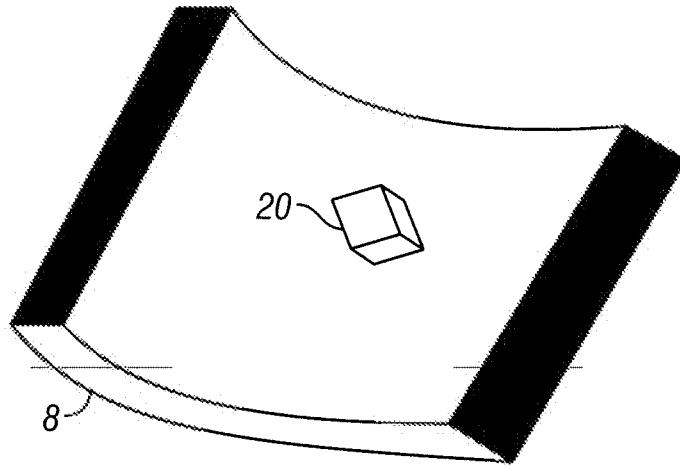


Figure 2A

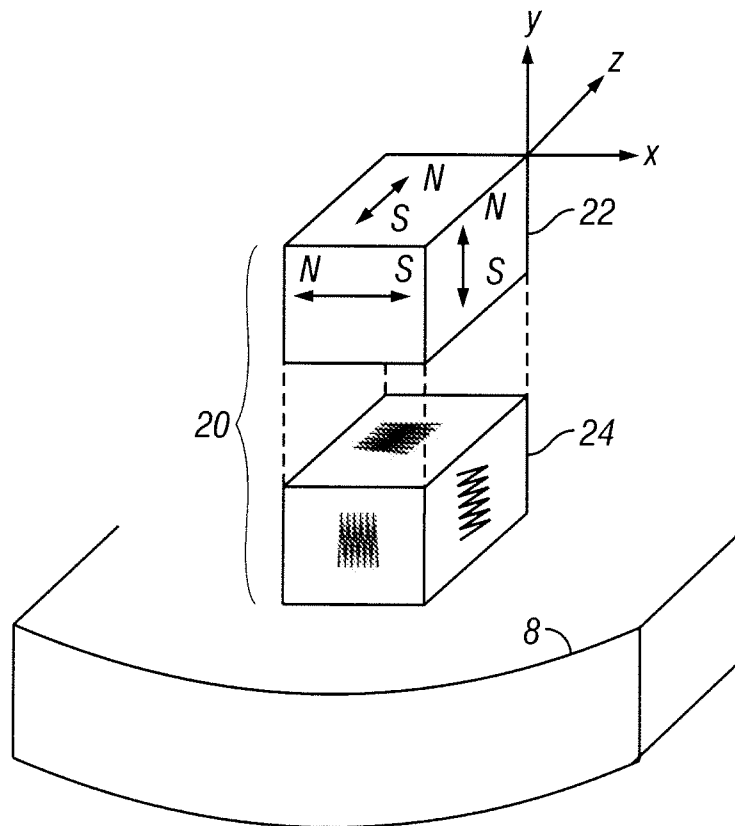


Figure 2B

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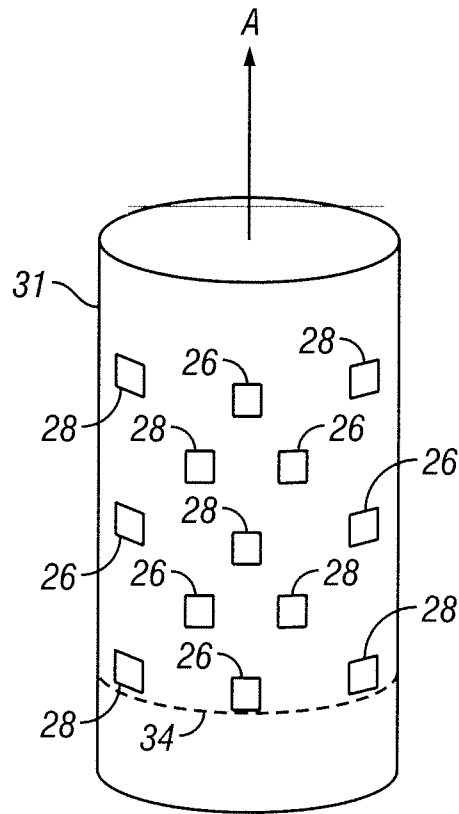


Figure 3

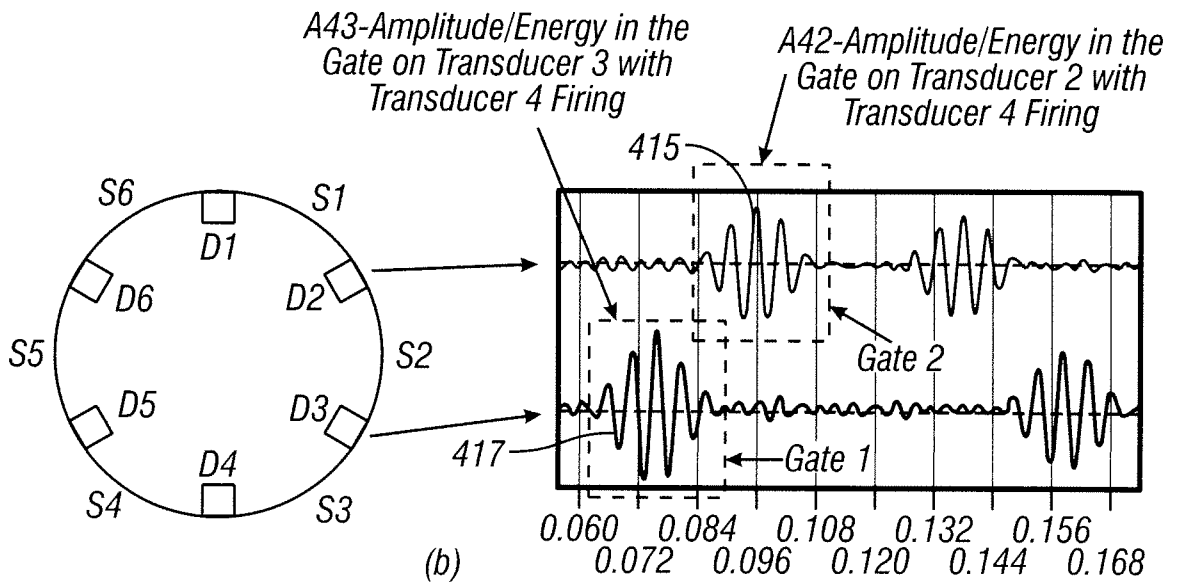
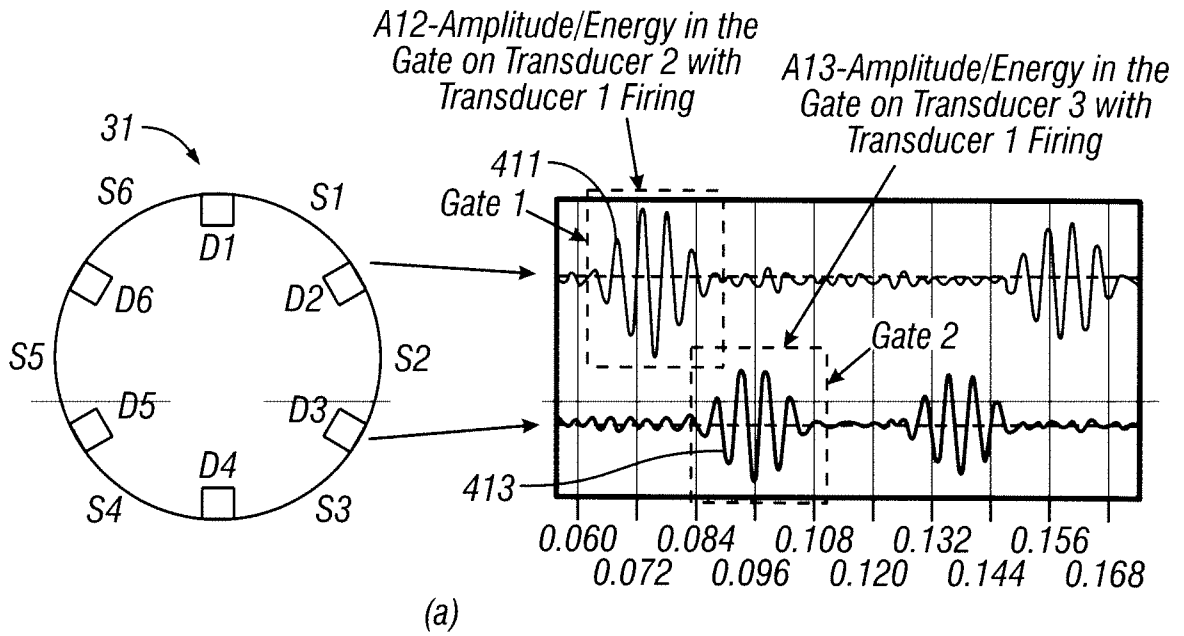


Figure 4

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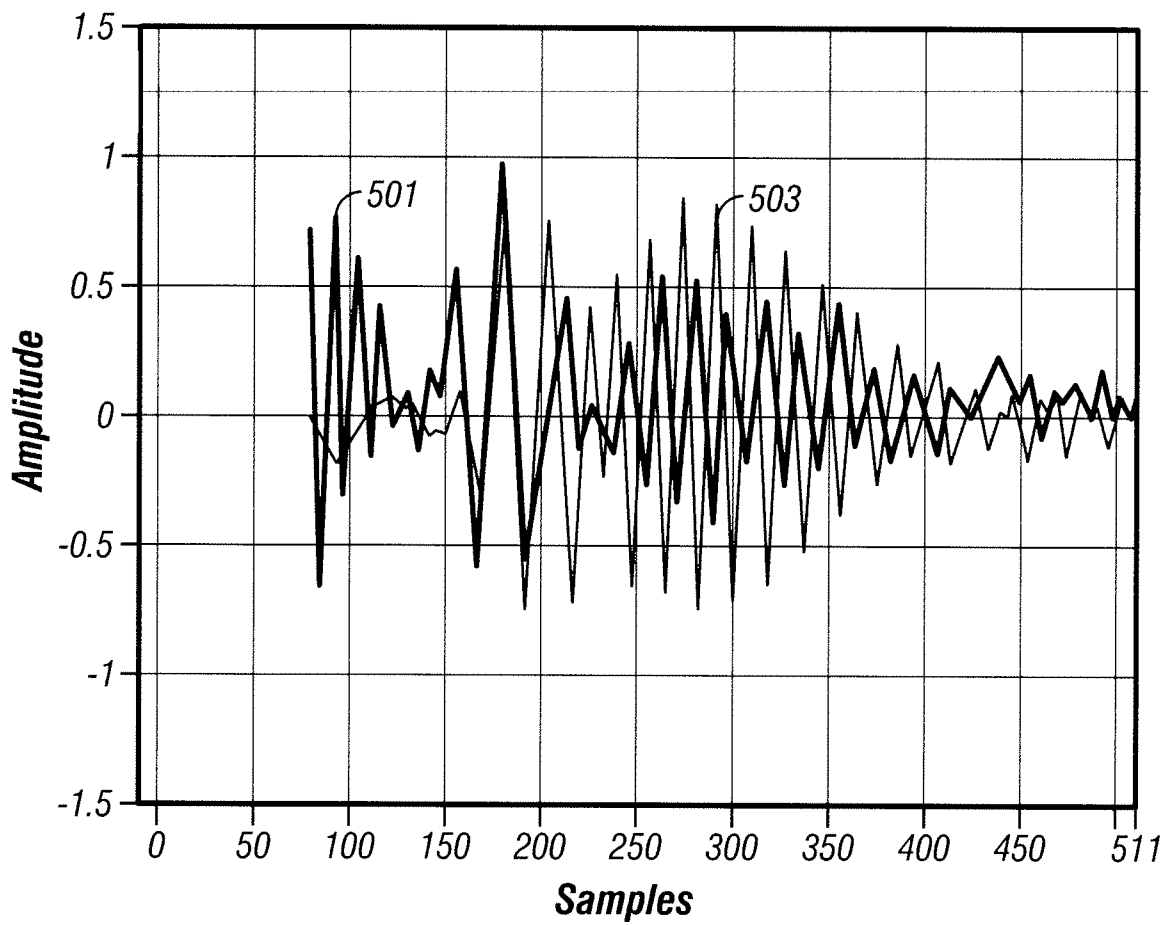


Figure 5

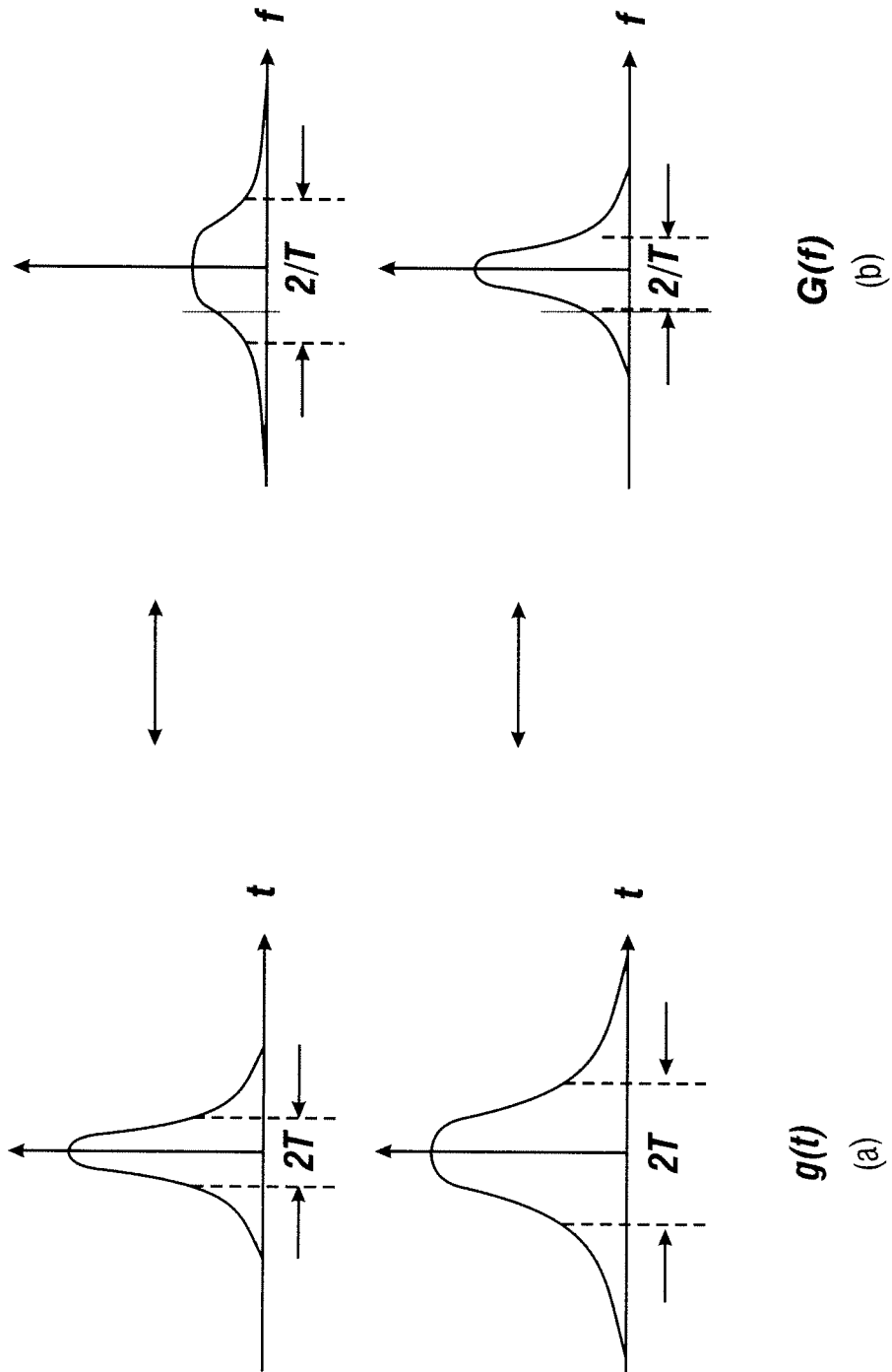


Figure 6

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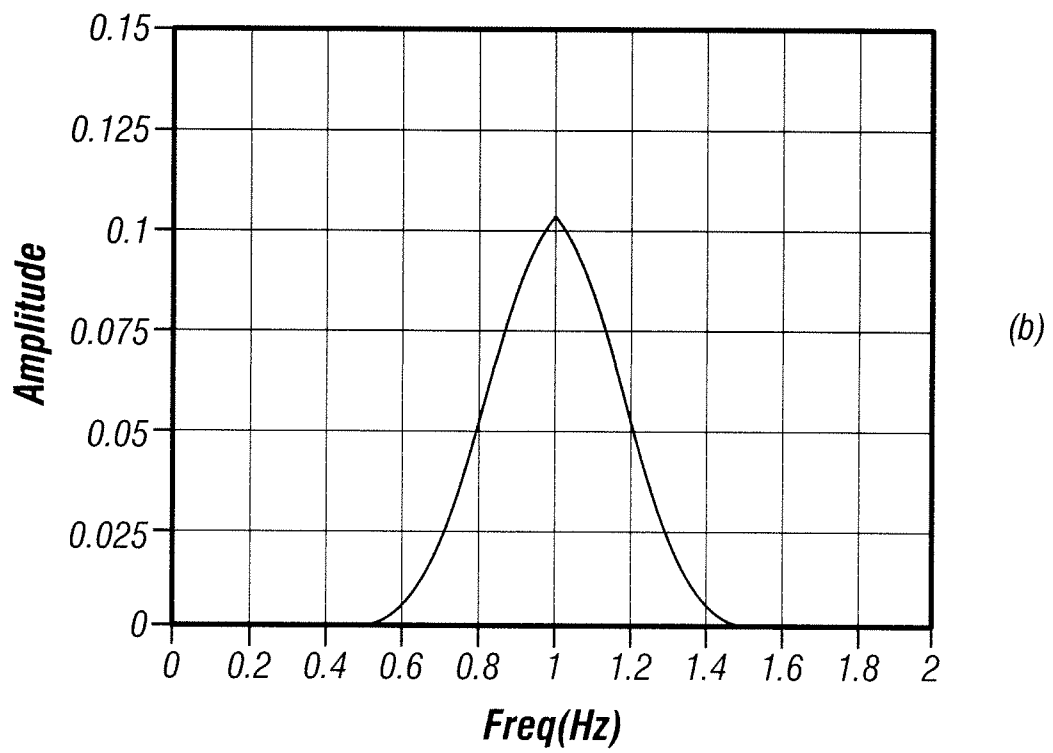
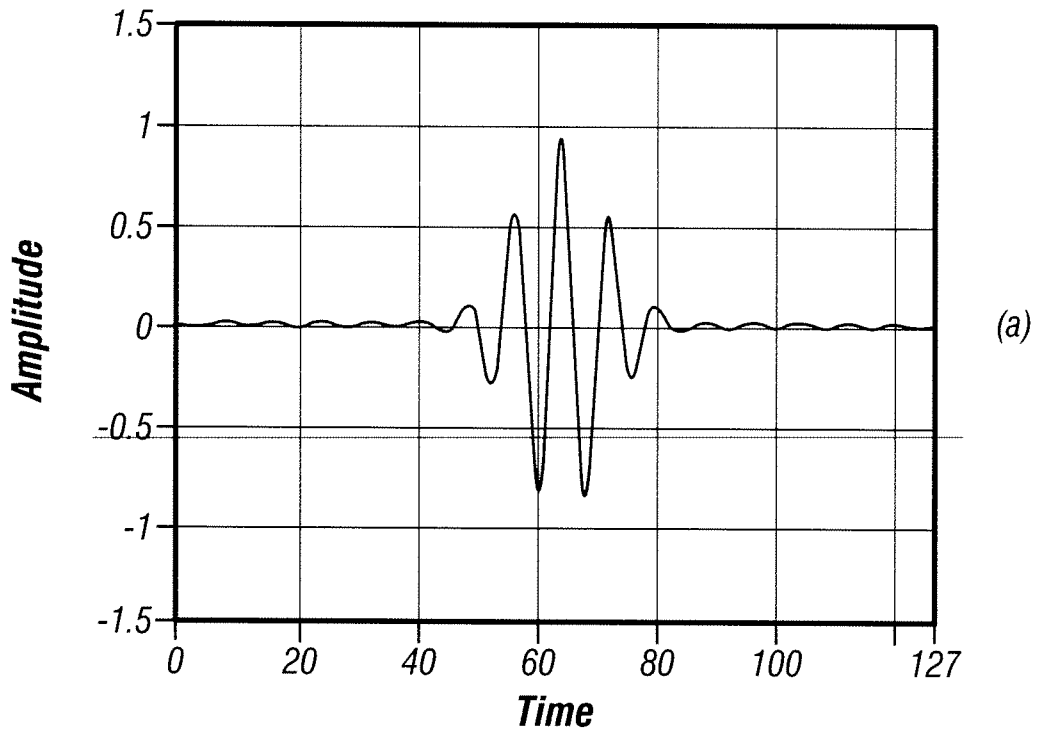


Figure 7

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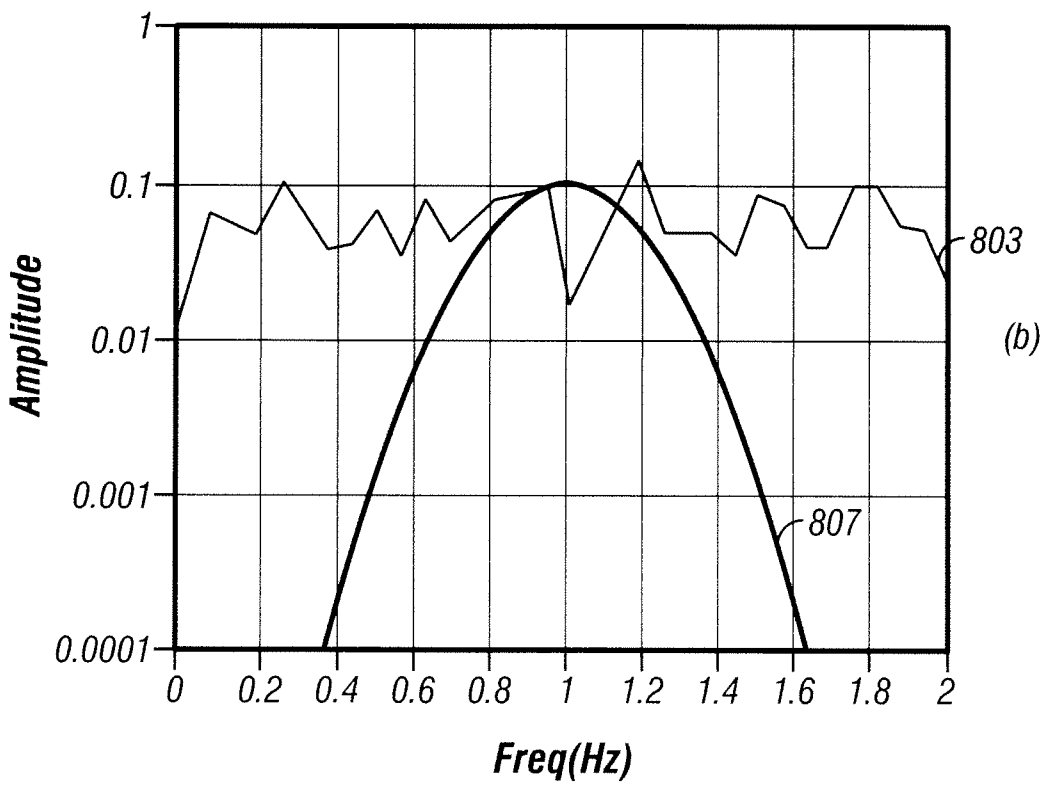
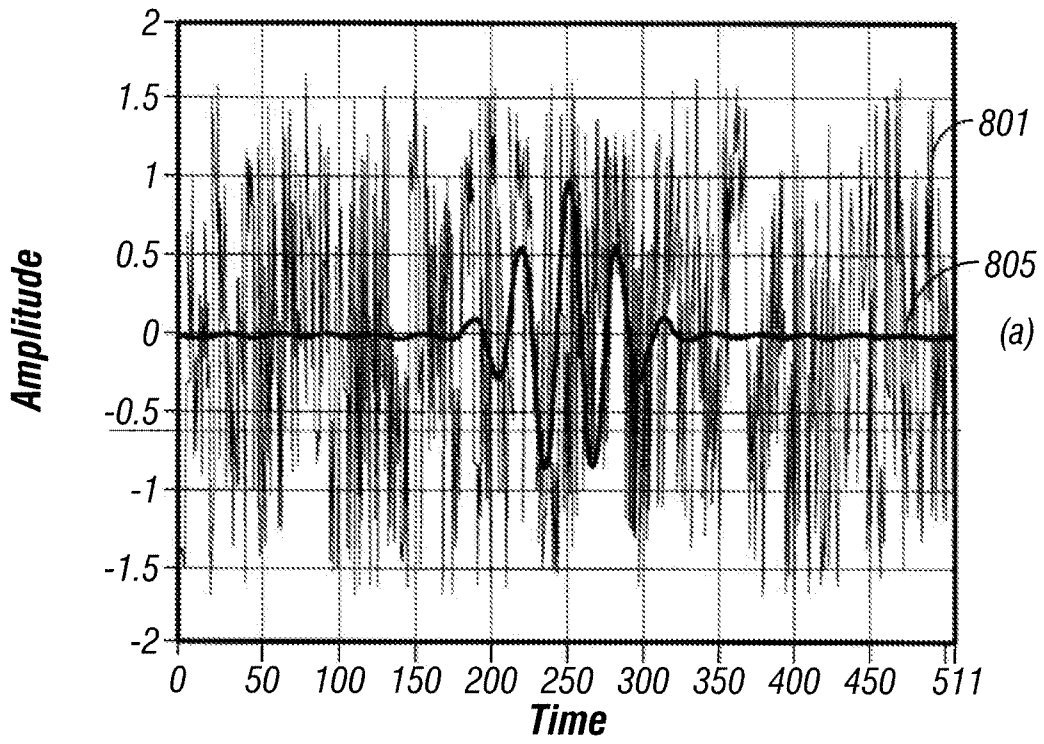


Figure 8

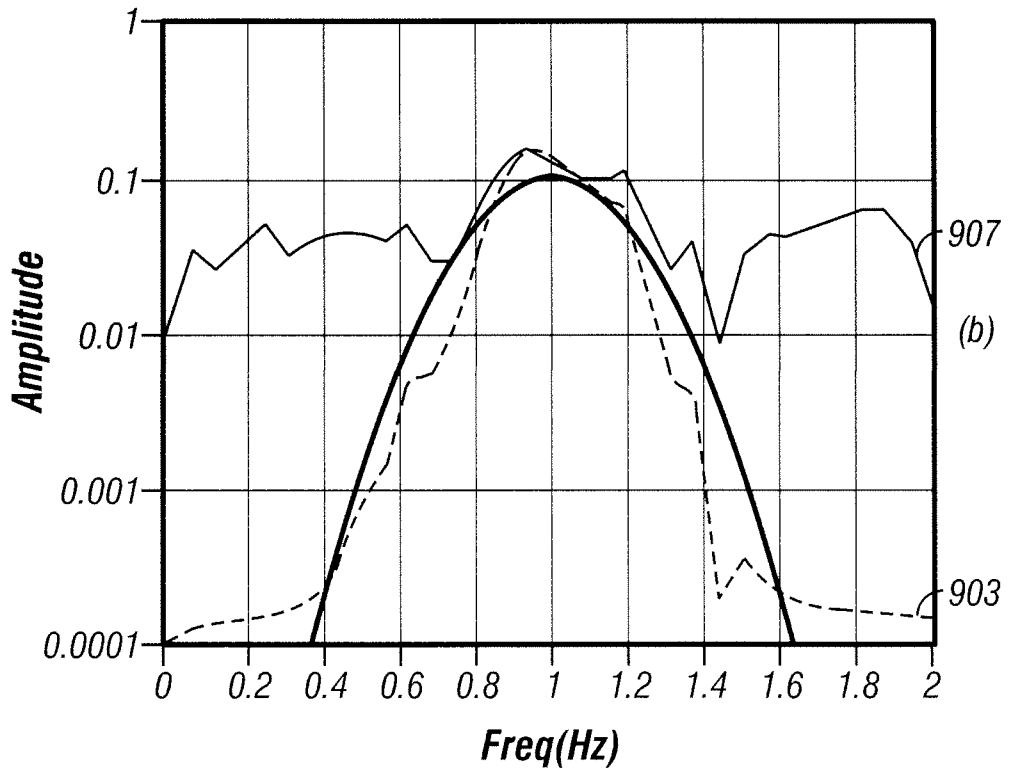
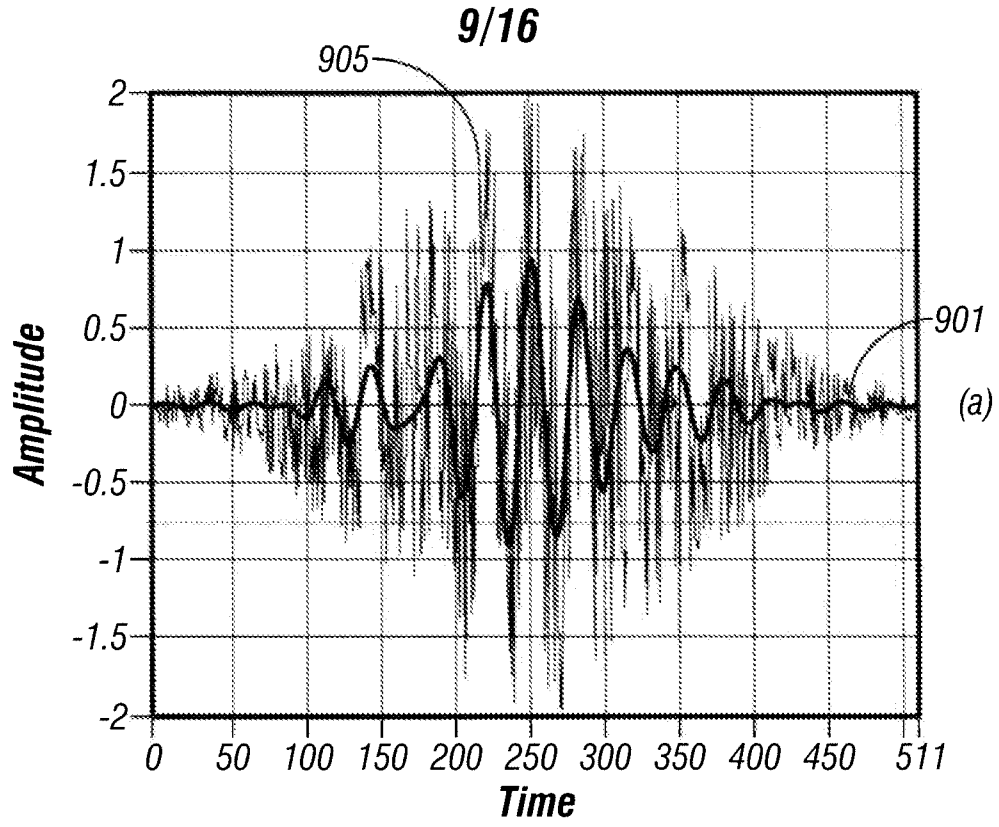


Figure 9

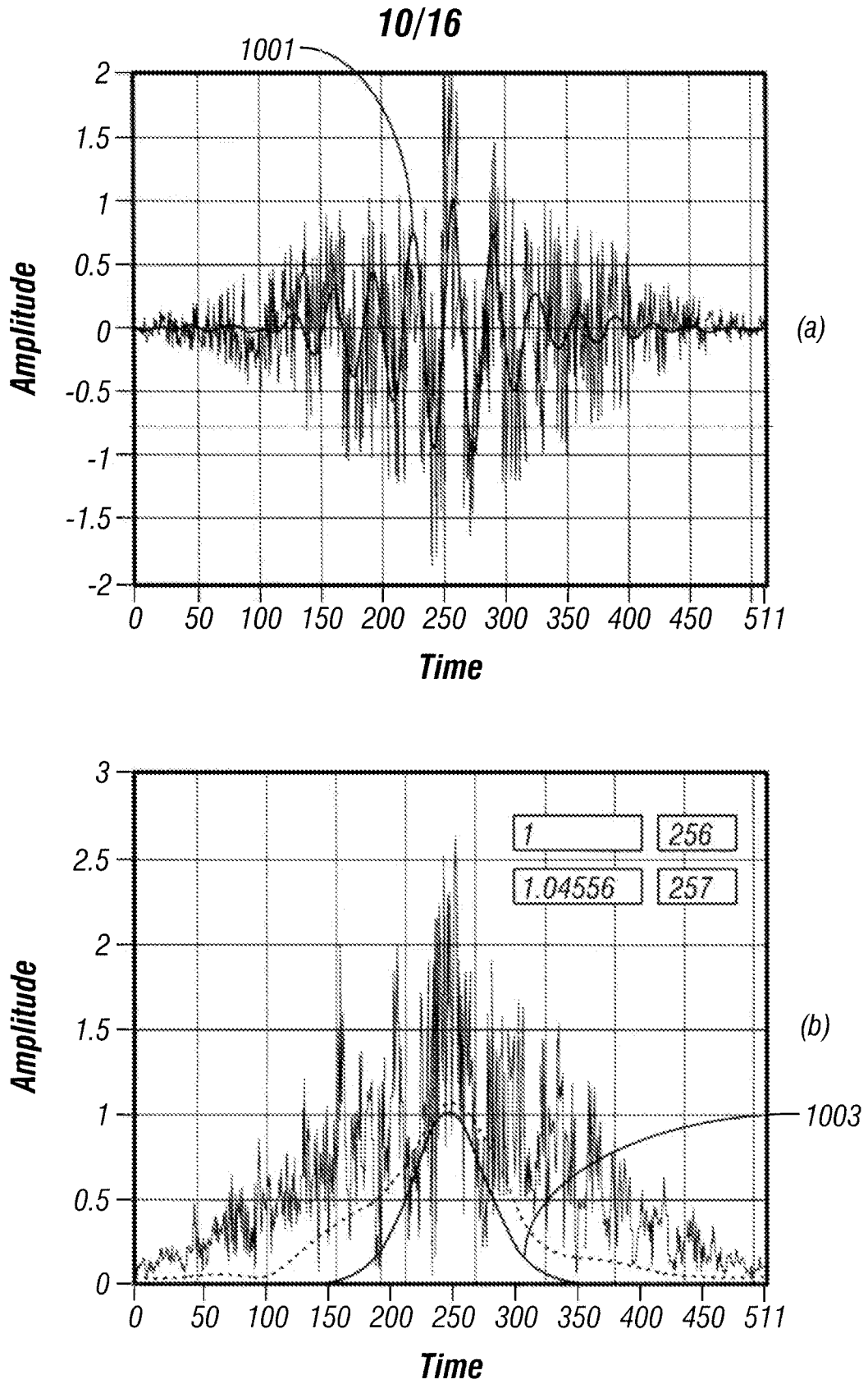


Figure 10

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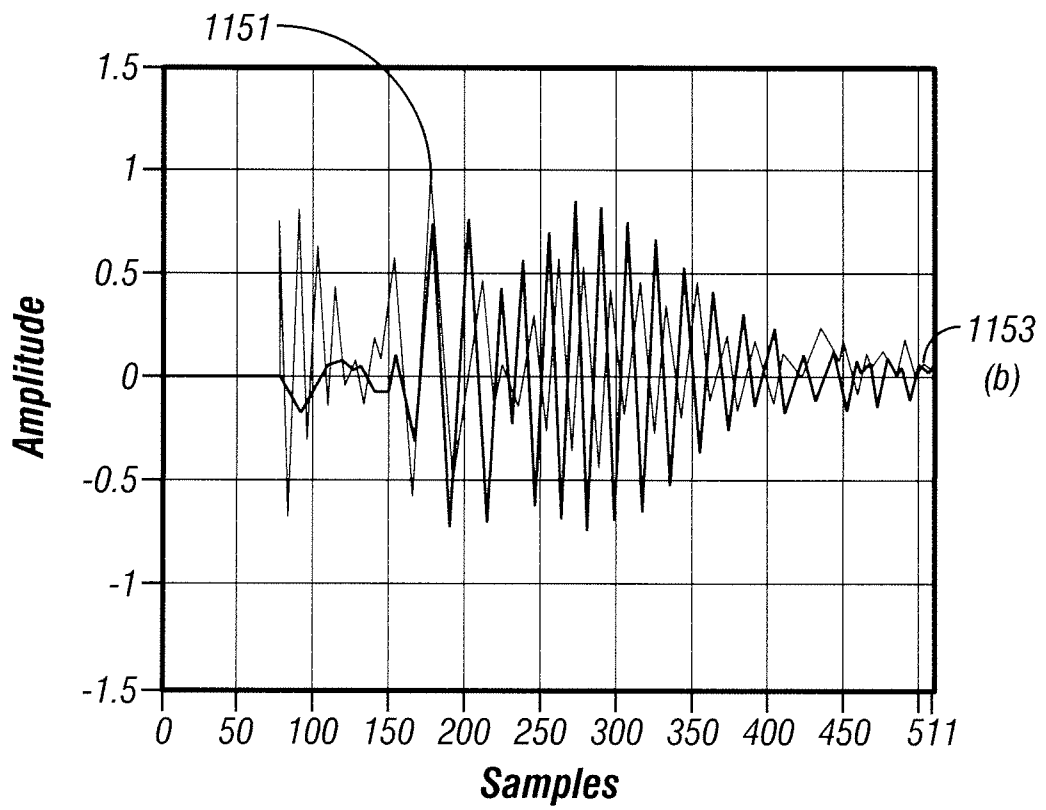
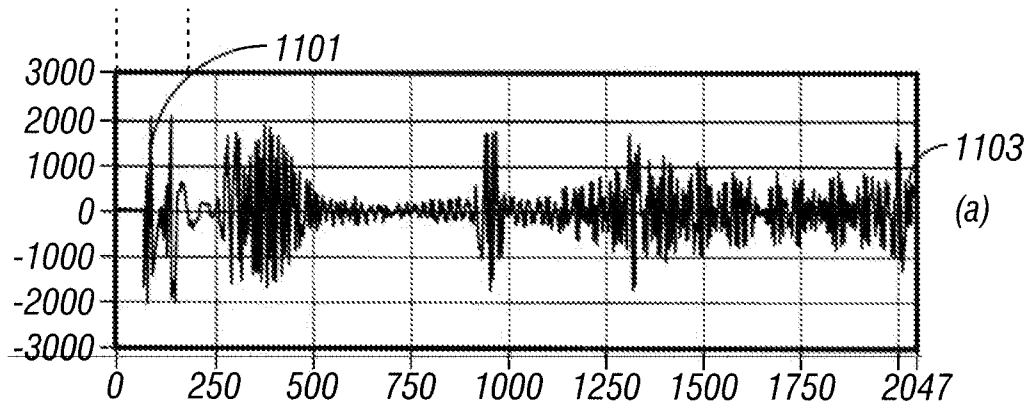


Figure 11

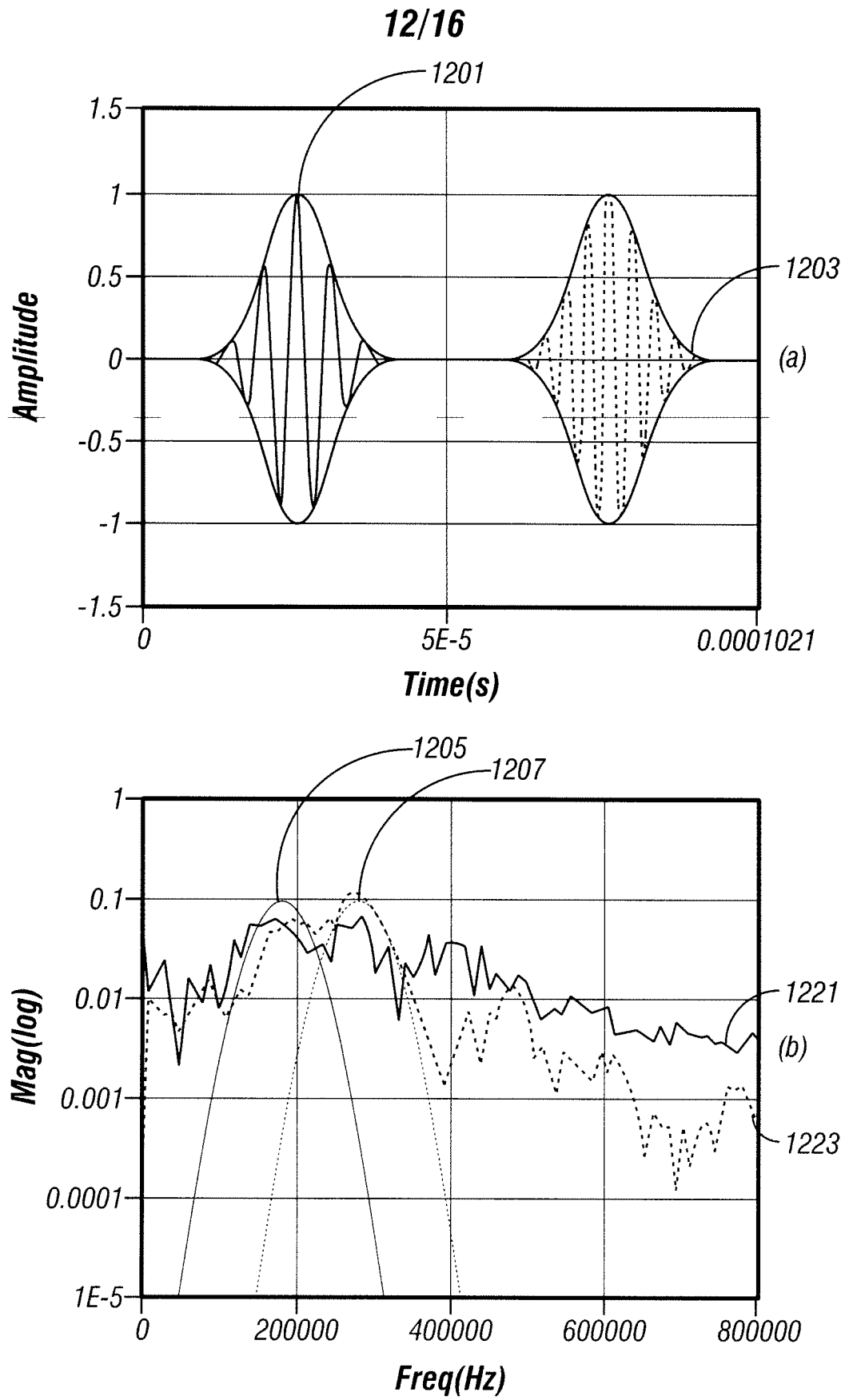


Figure 12

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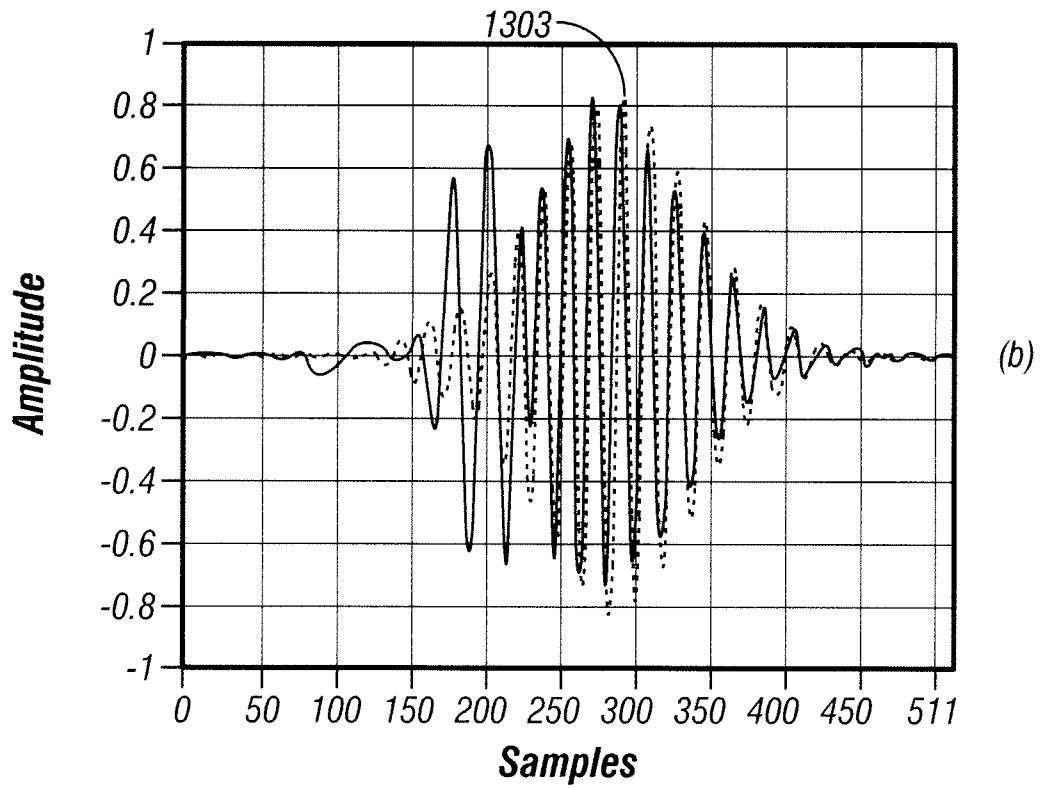
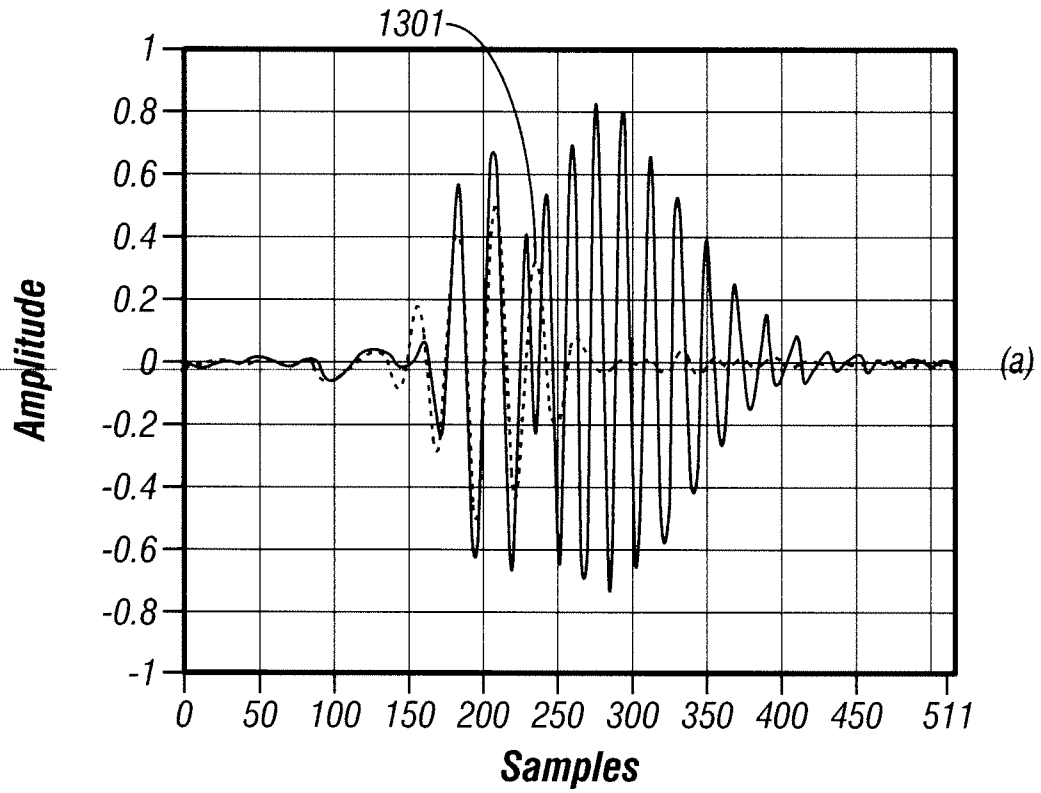


Figure 13

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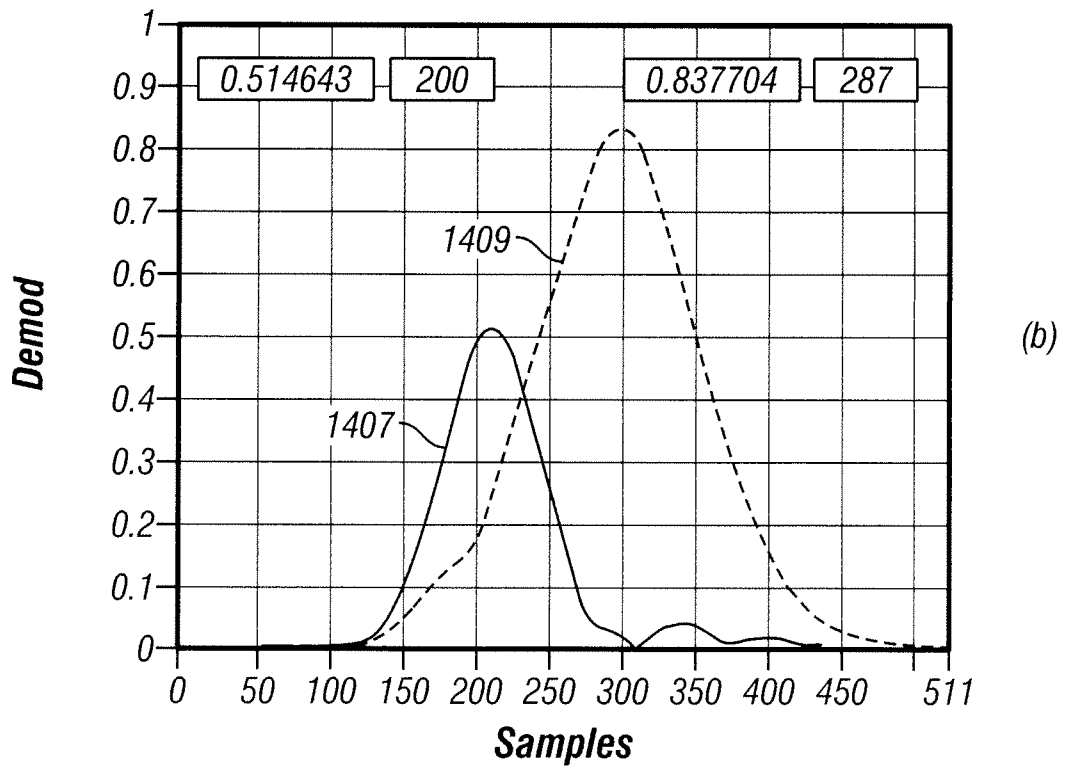
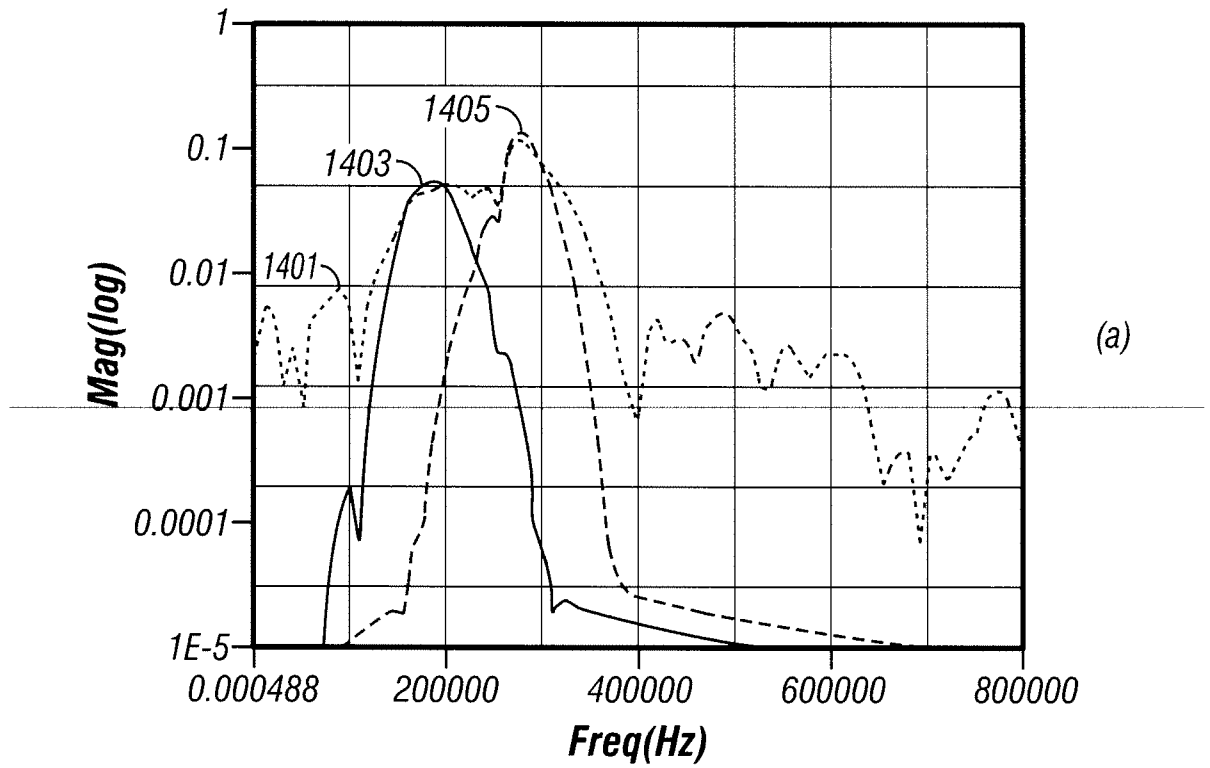


Figure 14

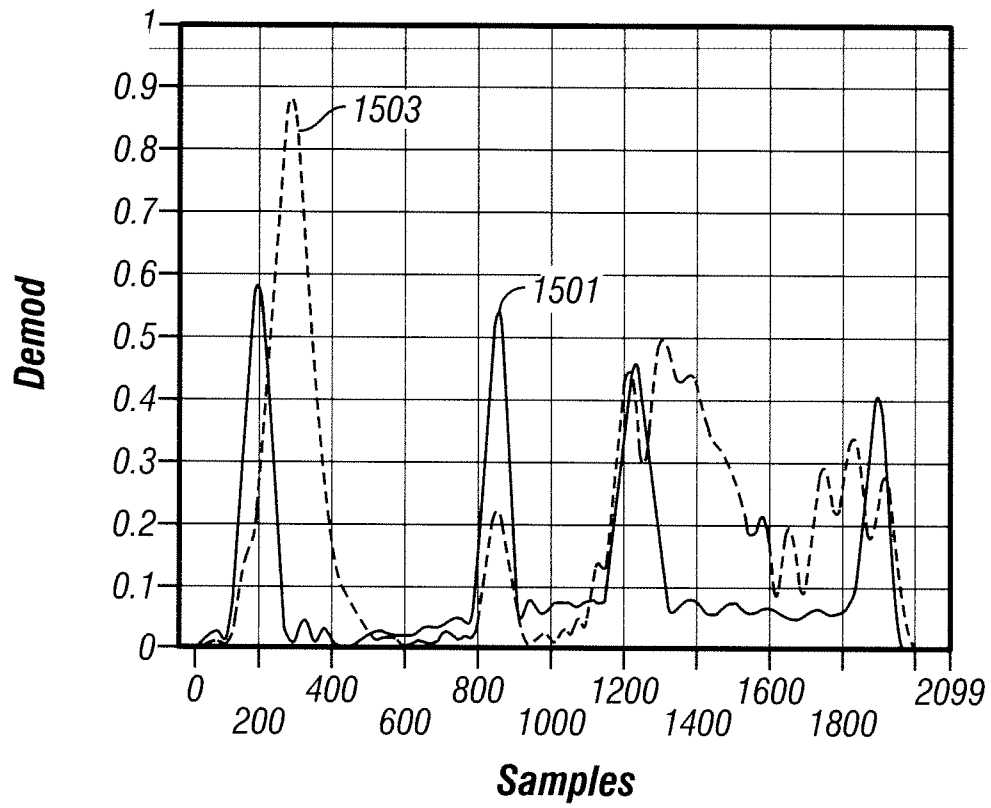


Figure 15

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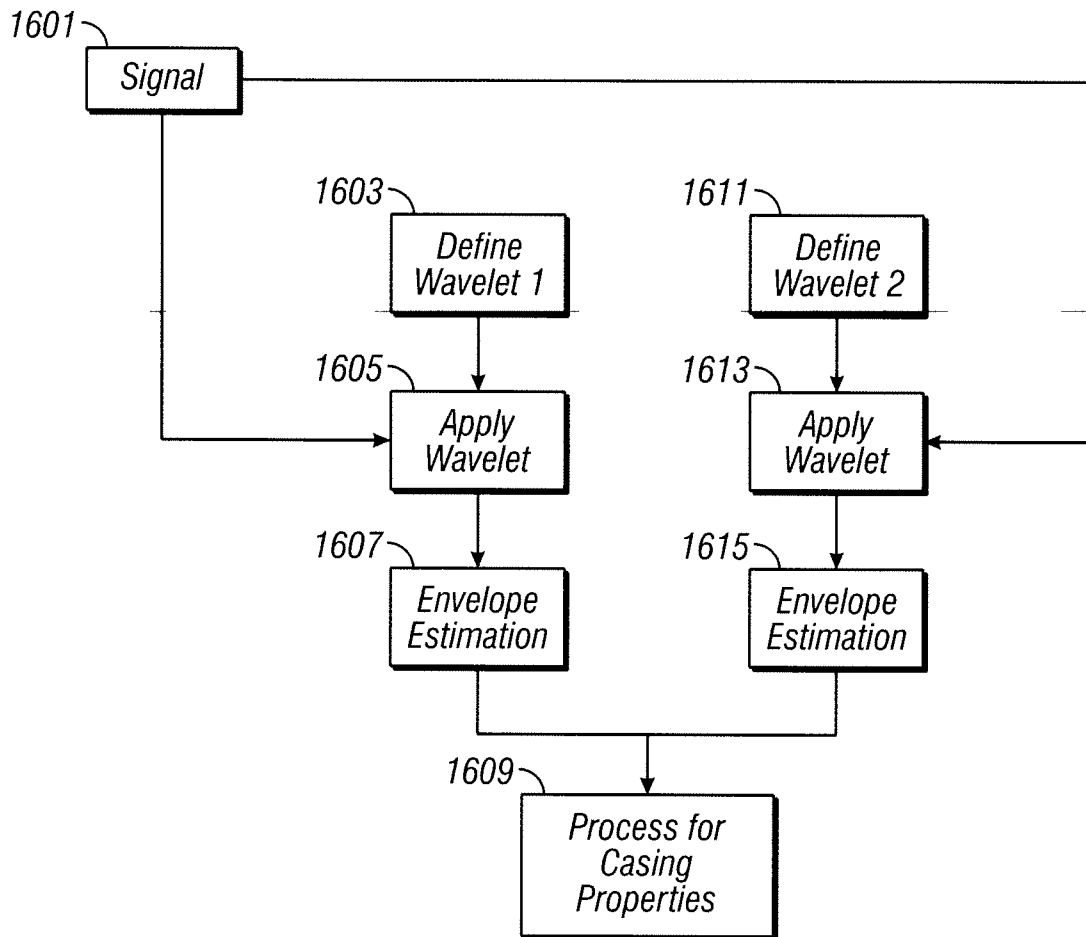


Figure 16