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- (71) **Applicant (for GB, JP, NL only):** **SCHLUMBERGER HOLDINGS LIMITED**; Craigmuir Chambers, PO Box 71, Road Town, Tortola (VG).
- (71) **Applicant (for AL, AU, AZ, BG, CO, CZ, DE, DK, GQ, GR, HU, ID, IE, IL, IT, KR, KZ, LT, MX, MY, NO, NZ, OM, PL, RO, RU, SI, SK, TD, TM, TN, TR, TT, UZ, ZA only):** **SCHLUMBERGER TECHNOLOGY B.V.** [NL/NL]; Parkstraat 83-89, NL-2514JG The Hague (NL).
- (71) **Applicant (for CA only):** **SCHLUMBERGER CANADA LIMITED** [CA/CA]; 7th Floor 525-3rd Avenue S.W., Eau Claire Place 1, Alberta, Calgary T2P OG 4 (CA).
- (71) **Applicant (for all designated States except AL, AU, AZ, BG, CA, CO, CZ, DE, DK, FR, GB, GQ, GR, HU, ID, IE, IL, IT, JP, KR, KZ, LT, MX, MY, NL, NO, NZ, OM, PL, RO, RU, SI, SK, TD, TM, TN, TR, TT, US, UZ, ZA):** **PRAD RESEARCH AND DEVELOPMENT LIMITED**; Craigmuir Chambers, PO Box 71, Road Town, Tortola (VG).
- (71) **Applicant (for FR only):** **SERVICES PETROLIERS SCHLUMBERGER** [FR/FR]; 42 rue saint Dominique, F-75007 Paris (FR).
- (72) **Inventor; and**
- (71) **Applicant (for US only):** **ZHARNIKOV, Timur Vyacheslavovich** [RU/RU]; Novoyasenevsky prosp., 22-1-299, Moscow, 117574 (RU).
- (72) **Inventors:** **SYRESIN, Denis Evgenievich**; Moskovskaya str., 10-37, Dubna, Moskovskaya obl., 141985 (RU). **FUKUHARA, Masafumi**; Sagamihra-shi, Chuo-ku, Fuchinobe 2-2-1, Kanagawa, 252-0206 (JP). **ENDO, Takeshi**; Sagamihra-shi, Chuo-ku, Fuchinobe 2-2-1, Kanagawa, 252-0206 (JP). **YAMAMOTO, Hiroaki**; Sagamihra-shi, Chuo-ku, Fuchinobe 2-2-1, Kanagawa, 252-0206 (JP).
- (74) **Agent:** **ARKHIPOVA, Vera Nikolaevna**; Technology Company Schlumberger, Pudovkina str., 13, Moscow, 119285 (RU).
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(54) **Title:** A METHOD FOR PROCESSING ACOUSTIC WAVEFORMS

(57) **Abstract:** A method for processing acoustic waveforms comprises acquiring acoustic waveforms in a borehole traversing a subterranean formation and transforming at least a portion of the acoustic waveforms to produce frequency domain signals. Then model dispersion curves are generated based on an anisotropic borehole-formation model having a set of anisotropic borehole-formation parameters and by specifying governing equations and using a matrix Riccati equation approach. The frequency-domain signals are back-propagating using the model dispersion curves to correct dispersiveness of the signals and coherence of the back-propagated signals is calculated. Alternatively the difference between the measured and the model dispersion curves is determined. Model parameters are iteratively adjusted until the coherence reaches a maximum or exceeds a selected value, or alternatively until the difference between the measured and the model dispersion curves becomes minimal or is reduced to below a selected value. Then at least a portion of the set of anisotropic borehole-formation parameters is obtained.

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A method for processing acoustic waveforms

Field of the invention

The invention relates generally to acoustic well logging. More particularly, this invention relates to acoustic well logging techniques useful in determining formation properties.

Background of the invention

In acoustic logging, a tool is lowered into a borehole and acoustic energy is transmitted from a source into the borehole and the formation. The acoustic waves that travel in the formation are then detected with an array of receivers. These waves are dispersive in nature, i.e. the phase slowness is a function of frequency. This function characterizes the wave and is referred to as a dispersion curve. A challenge for processing acoustic data is how to correctly handle the dispersion effect of the waveform data.

Important step in processing acoustic logging data a dispersion analysis, that is, its optimal decomposition in limited number of modes in frequency-wavenumber domain, for example, based on Prony's method (S. W. Lang et al., "Estimating slowness dispersion from arrays of sonic logging waveforms", *Geophysics*, v. 52, No.4. p. 530-544, 1987). That is, it tries to find best fit of the signal by a limited sum of complex exponents. Its results are further used to extract information about elastic properties of formation. One of the ways to do it is to compare measured dispersion curves with a reference dispersion curve calculated under certain assumptions.

Current reference dispersion curves are calculated in several ways. For isotropic and VTI (vertically transversely isotropic) formations an analytical solution for radially layered medium is available and can be used to calculate dispersion curves by mode-search type of routines (B. K. Sinha, S. Asvadurov,

“Dispersion and radial depth of investigation of borehole modes”, *Geophysical Prospecting*, v.52, p. 271, 2004). The limitation is that they require a circular borehole and are not available for anisotropic or irregular formations. Direct 3D modeling of wavefield can be employed (P.F. Daley, F. Hron, “Reflection and transmission coefficients for transversely isotropic media”, *Bulletin of the Seismological Society of America*, v.67, p. 661 1977; H.D. Leslie, C.J. Randall, “Multipole sources in boreholes penetrating anisotropic formations: numerical and experimental results”, *JASA*, v.91, p.12, 1992; R.K. Mallan et al., “Simulation of borehole sonic waveforms in dipping, anisotropic and invaded formations”, *Geophysics*, v.76, p. E127, 2011; M. Charara et al., “3D spectral element method simulation of sonic logging in anisotropic viscoelastic media”, *SEG Exp. Abs.*, v. 30, p.432, 2011). The problem of these methods is heavy computational requirements. A dispersion curve of a guided wave involves numerous model parameters. Even in the simplest case of a fluid-filled borehole without a tool, six parameters are needed to calculate the dispersion curve (i.e., a borehole size, formation P- and S-velocities and density, and fluid velocity and density). In an actual logging environment, other unknown parameters, such as changing fluid property, tool off-centering, formation alteration, etc., also alter the dispersion characteristics. Therefore a need remains for fast and efficient calculation of dispersion curves with allowance for arbitrary anisotropy, formation radial and azimuthal inhomogeneity (including radial profiling, borehole irregularity and stress-induced anisotropy, etc.) and tool eccentricity.

In principle, possible main steps of sonic logging and data processing are well known and documented, such as firing acoustic signal with the transmitter and obtaining waveforms at receivers, extracting low frequency asymptote of the dispersive signal, comparing with the model dispersion curves, etc. However, practical processing, which includes the step of

comparing the measured data with the modeled dispersion curves is currently limited to isotropic or TIV formations. Performing this step for other types of anisotropic formations (general anisotropy) is impractical because either the accuracy is not always sufficient or controllable (perturbation theory approach, etc.) or the computation time is prohibitively large (full 3D wavefield modeling, etc.). The proposed invention rectifies this deficiency and demonstrates the algorithm to solve this problem both accurately and in time, which is acceptable for practical purposes. Therefore, it allows the processing to be done for the completely new class of rock formations – arbitrary anisotropy with spatial variation. At the moment, it is not possible to do by any other means with acceptable accuracy and speed. As a result, it is drastic change in the capabilities of the existing process and makes for the whole new process. The capabilities include possibility of taking into account and treating formations of arbitrary anisotropy (arbitrary symmetry class), arbitrary radial and azimuthal variation of formation physical properties. Axial variation of properties can be, in principle, also taken into account. This completely new capability. Computational efficiency allows the proposed invention to be used for the well-site modeling of dispersion curves for general anisotropic formations, which is also new. The requirements for the computational power are drastically reduced (orders of magnitude both in time and hardware (memory, number of CPUs, etc.) requirements). For well-site or further processing significant improvement of computational efficiency implies increased turnaround time of data processing, interpretation, answer products, etc. This capability is new with respect to the currently available approaches.

Summary of the invention

In accordance with one embodiment of the invention, a method for processing acoustic waveforms comprises acquiring acoustic waveforms in a borehole traversing a subterranean formation, transforming at least a portion of the acoustic waveforms to produce frequency domain signals, generating model dispersion curves based on an anisotropic borehole-formation model having a set of anisotropic borehole-formation parameters by specifying governing equations and using a matrix Riccati equation approach, back-propagating the frequency-domain signals using the model dispersion curves to correct dispersiveness of the signals, calculating coherence of the back-propagated signals, iteratively adjusting model parameters until the coherence reaches a maximum or exceeds a selected value, outputting at least a portion of the set of anisotropic borehole-formation parameters.

A method for processing acoustic waveforms according to another embodiment of the invention comprises acquiring acoustic waveforms in a borehole traversing a subterranean formation, generating measured dispersion curves from the acquired waveforms, generating model dispersion curves based on an anisotropic borehole-formation model having a set of anisotropic borehole-formation parameters by specifying governing equations and using a matrix Riccati equation approach, determining a difference between the measured and the model dispersion curves, iteratively adjusting model parameters until the difference between the measured and the model dispersion curves becomes minimal or is reduced to below a selected value, outputting at least a portion of the set of anisotropic borehole-formation parameters.

Brief description of the drawings

Fig. 1 is a flow chart of a method of acoustic waveforms processing in accordance with the invention.

Detailed description of the invention

Acoustic data acquired with a logging tool are waveforms received by receivers. These waveforms include a large amount of data, which would need to be analyzed with an appropriate method to derive information related to formation properties.

Fig. 1 shows a schematic of a process in accordance with one embodiment of the invention for inverting borehole-formation parameters from acoustic waveforms. As shown, the acoustic waveforms are digitized (step 1 on Fig.1) and converted into the frequency domain by a suitable transformation (e.g., Fourier Transform (FT) or Fast Fourier Transform FFT) – step 2 on Fig. 1. According to steps 3 and 4 model dispersion curves are generated based on an anisotropic borehole-formation model having a set of anisotropic borehole-formation parameters by specifying governing equations and using a matrix Riccati equation approach.

Then, the frequency domain signals are back propagated using model dispersion curves to correct for dispersiveness of the signals (step 5 on Fig.1). The back propagation produces back-propagated waveforms, which are in the frequency domain.

Coherence of the back-propagated waveforms is then calculated. The processes of back propagation and computing coherence may be repeated iteratively by obtaining a new set of model dispersion curves that correspond to a different set of borehole-formation parameters (step 6 on Fig.1). These processes are repeated until the coherence meets a selected criterion, such as

reaching a maximum or exceeding a selected value. Then, the borehole-formation parameters are output.

Alternatively, measured dispersion curves can be measured from acquired waveforms. The difference between the measured and the model dispersion curves can be determined (step 5 on Fig.1) and iteration may be performed adjusting model parameters to produce the minimal difference between the measured and the model dispersion curves or reduce the difference between the measured and the model dispersion curves to below a selected value (step 6 on Fig.1). The choice of model parameters depends on the particular problem to be solved. For example, if the target is to evaluate elastic moduli of a formation assuming it to be homogeneous tilted transversely isotropic (TTI) one, possible parameters are 5 elastic moduli (C_{11} , C_{13} , C_{33} , C_{44} , C_{66}) and relative dip angle θ . Bulk modulus of a drilling mud can be either taken as known approximately or added to the list of model parameters depending on the processing algorithm. The densities are usually obtained from other measurements.

Then, some or all of the borehole-formation parameters corresponding to the model dispersion curves that produce the minimal difference between the measured and the model dispersion curves are output to provide information on formation properties (step 7 on Fig.1).

An example of one of the embodiments relates to determination of formation elastic moduli, for instance, 5 TTI parameters which are required for geomechanical applications like determination of well stability, etc. Formation density can be estimated from gamma logs and mud density can be measured or guessed with reasonable accuracy. Similarly, bulk modulus of the drilling mud can be either guessed or, in principle, measured in situ. Then the attenuation in the mud is disregarded and formation is assumed to be homogeneous TTI one. Therefore, one arrives at the problem of determination

one parameter of the TTI model (e.g. elastic moduli (C11, C13, C33, C55, C66) from the sonic logging measurement. To address this problem, the invention proposed in this patent is embodied as described below.

Sonic waveforms in a borehole are recorded as dependent on azimuth and vertical coordinate by ~~any standard~~ a typical logging tool. The recorded signals are digitized.

Dispersion curves are estimated from the measured data by any known method (see, for example, S. W. Lang et al., “Estimating slowness dispersion from arrays of sonic logging waveforms”, Geophysics, v. 52, No.4. p. 530-544, 1987).

Then the initial set of elastic parameters is defined. For example, one can start with the isotropic model whose moduli λ and μ are estimated from the speeds of shear and compressional waves, recorded by the logging tool.

$$\lambda = \rho(V_p^2 - 2V_s^2), \mu = \rho V_s^2$$

where V_p is a P-wave velocity, V_s is a shear-wave velocity, ρ is the density.

Then dispersion curves of borehole modes recorded by the tool (e.g. Stoneley, pseudo Rayleigh, dipole flexural, quadrupole modes, etc.) are modeled. The modeling process starts with specifying governing general elastodynamic equations:

$$-\rho\omega^2 u_i = \partial_j \sigma_{ij}$$

$$\sigma_{ij} = c_{ijkl} \varepsilon_{kl}$$

The Fourier series expansion is used for azimuthally and radially dependable tensor $c_{IJ}(r, \theta)$ (here the Voigt notation is used for the tensor c_{ijkl})

$$c_{IJ}(r, \theta) = \sum_{m=-\infty}^{\infty} c_{IJ}^{(m)}(r) e^{in\theta}$$

The solution of general elastodynamic problem formulation is expanded with respect to a set of basis functions in coordinates z, θ, t . For example, one can use harmonic functions:

$$\bar{u} = (u_r, u_\theta, u_z) = \int dk \int d\omega \sum_n \bar{u}_n(r, k, \omega) e^{i(kz+n\theta-\omega t)}$$

$$\hat{\sigma} = (\sigma_{rr}, \sigma_{r\theta}, \sigma_{rz}) = \int dk \int d\omega \sum_n \hat{\sigma}_n(r, k, \omega) e^{i(kz+n\theta-\omega t)}$$

$$\tilde{\sigma} = (\sigma_{\theta\theta}, \sigma_{zz}, \sigma_{\theta z}) = \int dk \int d\omega \sum_n \tilde{\sigma}_n(r, k, \omega) e^{i(kz+n\theta-\omega t)}$$

Introduction of expansions of vectors $\bar{u}$, $\hat{\sigma}$, $\tilde{\sigma}$ and elasticity tensor $c_{IJ}(r, \theta)$ into governing equations yields the formulation of the system of differential equations

$$\hat{\sigma}_n = \sum_{m=-\infty}^{\infty} (\hat{A}_{\partial u}(m) \partial_r \bar{u}_{n-m} + \hat{A}_u(n-m, m, k) \bar{u}_{n-m}),$$

$$\tilde{\sigma}_n = \sum_{m=-\infty}^{\infty} (\tilde{A}_{\partial u}(m) \partial_r \bar{u}_{n-m} + \tilde{A}_u(n-m, m, k) \bar{u}_{n-m}),$$

$$-\rho\omega^2 \mathbf{I} \bar{u}_n = \partial_r \hat{\sigma}_n + \hat{D}(n, k) \hat{\sigma}_n + \tilde{D}(n, k) \tilde{\sigma}_n$$

Matrices $\hat{A}_{\partial u}(m)$, $\hat{A}_u(m)$, $\tilde{A}_{\partial u}(m)$, $\tilde{A}_u(m)$, $\hat{D}(n, k)$ and $\tilde{D}(n, k)$ are the functions of $r, k, c_{IJ}^{(m)}(r)$, $m, n, \rho(r)$ and can be calculated both analytically and numerically.

This infinite system is considered and truncated by the consideration of the finite set of azimuthal harmonics $\{n_j\}$. This set is chosen in such a way to diminish the deviation between the calculated waveguide spectrum and the real one. After such the truncation and a certain algebraic reorganization of the system, the matrix telegrapher's equation can be written:

$$\partial_r \begin{pmatrix} \bar{U}_0 \\ \bar{S}_0 \end{pmatrix} = \begin{pmatrix} Q & \Lambda \\ -P & -S \end{pmatrix} \begin{pmatrix} \bar{U}_0 \\ \bar{S}_0 \end{pmatrix}$$

Here vectors $\bar{U}_0$ and $\bar{S}_0$ consist of the vectors $\bar{u}_{n_j}$ and $\hat{o}_{n_j}$, respectively. Matrices Q , Λ , S and P are the functions of the matrices $\hat{A}_{\partial u}(m)$, $\hat{A}_u(m)$, $\tilde{A}_{\partial u}(m)$, $\tilde{A}_u(m)$, $\hat{D}(n, k)$ and $\tilde{D}(n, k)$ and can be calculated analytically or numerically.

According the idea of matrix Riccati equation method formulation, one can use impedance matrix $Z(r)$ of the media, which is defined as follows:

$$\bar{S}_0 = Z(r)\bar{U}_0.$$

Introduction of this matrix into the matrix telegrapher's equation yields the formulation of the matrix Riccati equation for the impedance matrix $Z(r)$

$$d_r Z + Z\Lambda Z + ZQ + SZ + P = 0,$$

One of the possible approaches to calculate the spectrum or dispersion curves is the use of presented equation to formulate and solve boundary or initial value problem. For example, for inhomogeneous anisotropic layer with boundaries $r = r_0$ and $r = r_1$, surrounded by outer elastic media, one can introduce the numerical or analytical representations of impedance matrices of these outer media $Z(r_0)$ and $Z_{(L)}(r_1)$, as the functions of parameters $\{n_j\}$, k and ω . By solving this boundary value problem one arrive at the formulation of dispersion equation for the considered medium.

In general form, this dispersion equation is formulated as implicit function of the variables $\{n_j\}$, k and ω :

$$f(\{n_j\}, k, \omega) = 0$$

The roots of this equation, corresponding to the spectrum of the studied medium, can be calculated and classified by applying various well-known root-search routines, e.g. by using the parametric continuation method.

The generated model dispersion curves are compared with the dispersion curves estimated from the measured data. If there is no difference, initial approximation is considered to be good and the formation parameters

are found ($C_{11} = \lambda + 2\mu$, $C_{13} = \lambda$, $C_{33} = \lambda + 2\mu$, $C_{55} = \mu$, $C_{66} = \mu$). Otherwise elastic moduli (C_{11} , C_{13} , C_{33} , C_{55} , C_{66}) are adjusted and one goes back to step of modeling dispersion curves.

Modeling and comparison are repeated, until model dispersion curves are considered to match well with the experimental data. At this moment the elastic moduli, for which this match is observed, are considered to describe the formation.

Suggested method is reasonably fast and does not require heavy computational facilities, it works in reasonably wide range of parameters, is sufficiently accurate and robust.

Suggested method affects a number of applications, raising them to the new technology level (which is currently limited due to absence of borehole modes' dispersion curve computation algorithms for anisotropic formations, which are both accurate and computationally efficient). Such applications include, but are not limited to:

- Obtaining model dispersion curve based on an anisotropic borehole-formation model (including arbitrary anisotropy; arbitrary radial and azimuthal inhomogeneity; arbitrary spatial inhomogeneity) having a set of anisotropic borehole-formation parameters. The algorithm allows for fast and computationally efficient calculation of dispersion curves for waveguides (including boreholes) with allowance for arbitrary anisotropy, radial and azimuthal inhomogeneity of waveguide properties (including layering, radial profiling, borehole irregularity and stress-induced anisotropy, etc.) and tool and/or layers eccentricity.

- Solution of inverse problem and extracting properties of formation by comparing measured dispersion curves with those modeled by the proposed method. It includes radial profiling for cased and open boreholes in anisotropic formation.

- Survey parameter decision/optimization at wellsite or prior to the job.
- Estimation of mode contamination in complex borehole environments and vice versa evaluation of borehole parameters from mode contamination information.
- Quality control of the results obtained in previous items.
- Determination of elastic moduli. E.g. TTI parameters.
- Check of and comparison of the modeled dispersion curves with the results of dispersion analysis of measured data.
- The interpretation of sonic data. Determination of the elastic moduli, identification of local parameter variations and verification of the results.
- Well development decisions. E.g. geomechanical applications like well stability, etc. Also for example for horizontal wells, gas shale wells, etc. For example, local variations of elastic moduli can be used to plan and improve completion decisions, geomechanical decisions, fracturing jobs design.
- Possibly for LWD shear evaluation from monopole pseudo Rayleigh wave.

Claims

1. A method for processing acoustic waveforms comprising:

acquiring acoustic waveforms in a borehole traversing a subterranean formation,

transforming at least a portion of the acoustic waveforms to produce frequency-domain signals,

generating model dispersion curves based on an anisotropic borehole-formation model having a set of anisotropic borehole-formation parameters by specifying governing equations and using a matrix Riccati equation approach,

back-propagating the frequency-domain signals using the model dispersion curves to correct dispersiveness of the signals,

calculating coherence of the back-propagated signals, iteratively adjusting model parameters until the coherence reaches a maximum or exceeds a selected value, and

outputting at least a portion of the set of anisotropic borehole-formation parameters.

2. Method of claim 1 wherein acoustic waveforms comprise signals from a Stoneley mode, a dipole mode, or a quadrupole mode.

3. Method of claim 1 wherein acoustic waveforms are transformed into the frequency domain signals by Fourier transforming or Fast Fourier Transforming.

4. A method for processing acoustic waveforms comprising:

acquiring acoustic waveforms in a borehole traversing a subterranean formation,

generating measured dispersion curves from the acquired waveforms,

generating model dispersion curves based on an anisotropic borehole-formation model having a set of anisotropic borehole-formation parameters

by specifying governing equations using a matrix Riccati equation approach, determining a difference between the measured and the model dispersion curves,

iteratively adjusting model parameters until the difference between the measured and the model dispersion curves becomes minimal or is reduced to below a selected value, and

outputting at least a portion of the set of anisotropic borehole-formation parameters.

5. Method of claim 4 wherein acoustic waveforms comprise signals from a Stoneley mode, a dipole mode, or a quadrupole mode.

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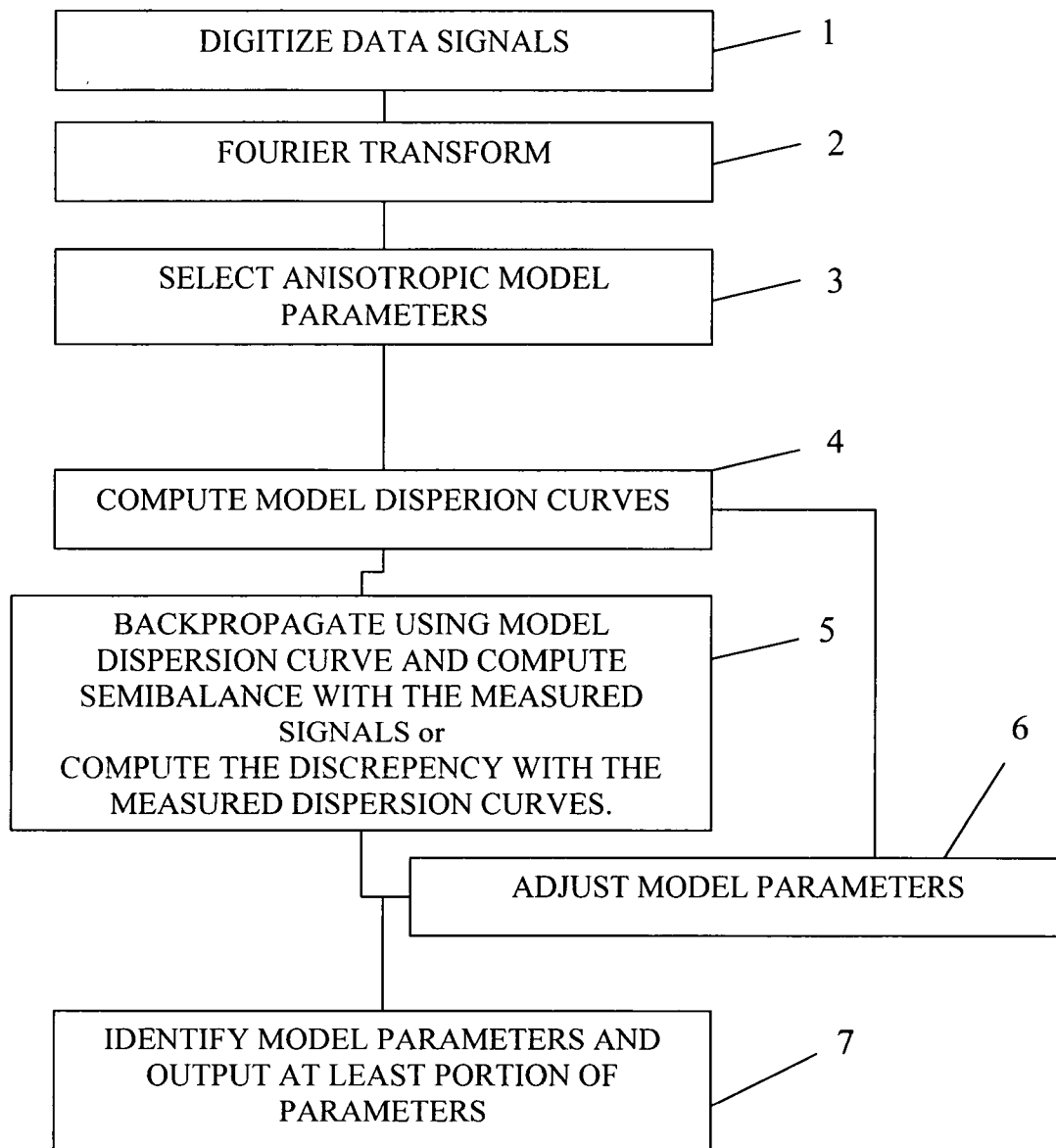


Fig.1

INTERNATIONAL SEARCH REPORT

International application No.

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A. CLASSIFICATION OF SUBJECT MATTER

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According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

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Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

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C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 2006/0120217 A1 (PETER T. WU. et al.) 08.06.2006	1-5
A	RU 2361241 C2 (SCHLUMBERGER TECHNOLOGY B.V.) 10.07.2009	1-5
A	RU 2402045 C1 (SCHLUMBERGER TECHNOLOGY B.V.) 20.10.2010	1-5
A	RU 2222807 C2 (GOSUDARSTVENNOE OBRAZOVATELNOE UCHREZHDENIE VYSSHEGO PROFESSIONALNOGO OBRAZOVANIYA YUZHNO-ROSIYSKIY GOSUDARSTVENNY TEKHNIЧЕСКИЙ УНИВЕРСИТЕТ (NOVOCHERKASSKIY POLITEKHNIЧЕСКИЙ INSTITUT)) 27.01.2004	1-5
A	WO 2008/142500 A2 (SCHLUMBERGER TECHNOLOGY B.V.) 27.11.2008	1-5

☐ Further documents are listed in the continuation of Box C.☐ See patent family annex.

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"O" document referring to an oral disclosure, use, exhibition or other means		
"P" document published prior to the international filing date but later than the priority date claimed		

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Name and mailing address of the ISA/ FIPS
Russia, 123995, Moscow, G-59, GSP-5,
Berezhkovskaya nab., 30-1

Facsimile No. +7 (499) 243-33-37

Authorized officer

I. Konycheva

Telephone No. (499) 240-25-91