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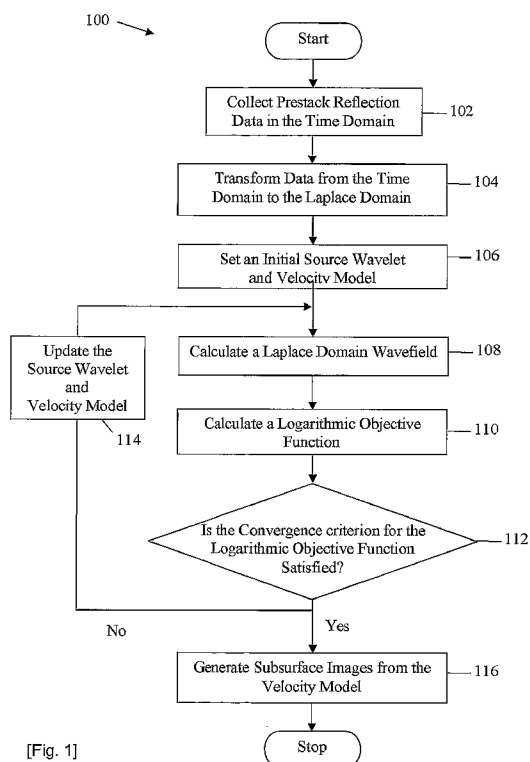
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(54) Title: METHOD FOR VELOCITY ANALYSIS USING WAVEFORM INVERSION IN LAPLACE DOMAIN FOR GEO-PHYSICAL IMAGING



[Fig. 1]

(57) Abstract: A Laplace transform system comprising a processor, a measured time domain wavefield, a velocity model, and Laplace damping constants, wherein the processor is programmed to calculate a substantially about zero frequency component of a Fourier transform of a time domain damped wavefield, wherein the time domain damped wavefield is damped by the Laplace damping constants to obtain long wavelength velocity information for deeper subsurface regions.

Description

METHOD FOR VELOCITY ANALYSIS USING WAVEFORM INVERSION IN LAPLACE DOMAIN FOR GEOPHYSICAL IMAGING

Technical Field

- [1] This invention is related to Method for Velocity Analysis Using Waveform Inversion in Laplace Domain for Geophysical Imaging.

Background Art

- [2] Seismic imaging is used for various purposes, such as for searching for subsurface oil and gas reservoirs. In seismic imaging, a physical subsurface image or a related subsurface information model, such as the velocity model, is constructed from collected seismic measurement data. One type of collected seismic measurement data is prestack reflection data in the time domain. Generally, to collect prestack reflection data, acoustic or elastic waves are sent into the underground using a number of specialized sources. The sources are typically dispersed over the top surface to cover a certain area of interest. The reflected seismic waves from the subsurface are then collected at the top surface using a number of specialized receivers that cover the area of interest. The subsurface image, or the related velocity model, is then constructed by processing the prestack reflection data in some form.
- [3] Recently, with the rapid development of computing hardware, mathematical waveform inversion of prestack reflection data has reemerged as one form of processing to generate subsurface information from an initial guess model. Waveform inversion of prestack reflection data has been attempted in both the time domain and the frequency domain, arriving to no conclusions on which approach is best. Both approaches have been applied with degrees of success to synthetic data generated by known theoretical benchmark models. However, a successful implementation of waveform inversion for real collected prestack reflection data remains elusive. One obstacle for a successful implementation is the absence of low frequency components in real data, which makes it difficult to resolve

long wavelength velocity models. Another reason that prevents a successful waveform inversion of real data is the possibility of non-unique solutions for subsurface images or velocity models.

Disclosure

Technical Solution

- [4] In one embodiment, a Laplace transform system is provided comprising a processor, a measured time domain wavefield, a velocity model, and Laplace damping constants, wherein the processor is programmed to calculate a substantially about zero frequency component of a Fourier transform of a time domain damped wavefield, wherein the time domain damped wavefield is damped by the Laplace damping constants to obtain long wavelength velocity information for deeper subsurface regions.
- [5] In another embodiment, a Laplace domain inversion system is provided. The system comprises a processor; a damped recorded wavefield in a Laplace domain; a wave equation; an objective function; and a velocity model, wherein the processor is programmed to solve the wave equation in the Laplace domain, minimize the objective function, and calculate the velocity model that corresponds to the damped recorded wavefield to analyze subsurface regions.
- [6] In still another embodiment, a method is provided for analyzing subsurface regions, comprising receiving collected prestack reflection data in a time domain transforming the time domain prestack reflection data to Laplace domain reflection data; initializing a preliminary velocity model that represents a subsurface structure calculating one of a logarithmic, an integral, and a power objective function; verifying whether the objective function satisfies a convergence criterion; updating the velocity model if the convergence criterion is not met; and generating a subsurface image from the velocity model if the convergence criterion is met to analyze subsurface regions.
- [7] These and other features will be more clearly understood from the following detailed description taken in conjunction with the accompanying drawings and claims.

Description of Drawings

- [8] For a more complete understanding of this disclosure, reference is now made to the following brief description, taken in connection with the accompanying drawings and detailed description, wherein like reference numerals represent like parts.
- [9] FIG. 1 illustrates an embodiment of a Laplace domain waveform inversion method.
- [10] FIG. 2A illustrates an embodiment of an undamped time domain wavefield.
- [11] FIG. 2B illustrates an embodiment of a damped time domain wavefield.
- [12] FIG. 2C illustrates another embodiment of a damped time domain wavefield.
- [13] FIG. 3 illustrates an embodiment of objective functions.
- [14] FIG. 4 illustrates an exemplary general-purpose computer system suitable for implementing the several embodiments of the disclosure.
- [15] *FIG. 5 illustrates the overall configuration of a subsurface structure imaging device based on Laplace domain waveform inversion according to an embodiment of the present invention; and
- [16] FIG. 6 illustrates a data processing unit of FIG. 5.

Best Mode

- [17] It should be understood at the outset that although an illustrative implementation of one or more embodiments are provided below, the disclosed systems and/or methods may be implemented using any number of techniques, whether currently known or in existence. The disclosure should in no way be limited to the illustrative implementations, drawings, and techniques illustrated below, including the exemplary designs and implementations illustrated and described herein, but may be modified within the scope of the appended claims along with their full scope of equivalents.
- [18] Disclosed herein is a waveform inversion method in the Laplace domain for constructing a subsurface velocity model from prestack reflection data. A wavefield in the Laplace domain may be equivalent to a zero or near zero frequency component of a damped wavefield in the time domain. Therefore, an inversion of a wavefield in the Laplace

domain may share similar properties of waveform inversion with the zero or near zero frequency component of an undamped wavefield in the time domain. The waveform inversion for the zero or near zero frequency component of an undamped wavefield in the time domain may be equivalent to inverting a Poisson's equation. Thus, such as the case of inverting a Poisson's equation, the waveform inversion in the Laplace domain may be robust and may resolve long wavelength velocity models. In comparison to waveform inversion in the frequency domain, the Laplace domain inversion method may result in a smoother logarithmic, integral, or power objective function, wherein the method converges to a correct solution even if the initial velocity model is far from the true model. Furthermore, the waveform inversion in the Laplace domain may be optimized by adjusting the damping constant in order to resolve deep or shallow parts of the velocity model. Decreasing the damping constant of the wavefield may be suitable for resolving a long wavelength velocity model for deeper regions, and increasing the damping constant may be better suited for resolving the velocity model from shallower regions.

- [19] FIG. 1 illustrates an embodiment of a Laplace domain waveform inversion method 100. The Laplace domain waveform inversion method 100 may receive collected prestack reflection data in the time domain that represents a true underground structure. The Laplace domain waveform inversion method 100 may transform the time domain prestack reflection data to Laplace domain reflection data. The Laplace domain waveform inversion method 100 may initialize a preliminary velocity model that represents the subsurface structure based on predetermined factors. The method 100 may then use both the Laplace transformed collected data and the preliminary velocity model to calculate a logarithmic, integral, or power objective function, which is a measure of the degree of similarity between the collected data and modeled data corresponding to the preliminary velocity model. The method 100 may then verify if the logarithmic, integral, or power objective function satisfies a convergence criterion. If the logarithmic, integral, or power objective function does not satisfy the convergence criterion, the previous velocity model may be

updated and then used along with the Laplace transformed data to calculate a new logarithmic, integral, or power objective function. The method 100 may check again if the new logarithmic, integral, or power objective function satisfies the convergence criterion. If the convergence criterion is not satisfied, the process of updating the velocity model and calculating a new logarithmic, integral, or power objective function may be repeated. Once the logarithmic, integral, or power objective function satisfies the convergence criterion, the iteration ends and the last updated velocity model may represent accurately the true subsurface velocity model. The method 100 may use the final velocity model to generate a subsurface image and the method ends. As well as calculating the velocity model, in some embodiments, a source wavelet that may be calculated. Each of the blocks of the Laplace domain waveform inversion method 100 is discussed in detail below.

[20] The Laplace domain waveform inversion method 100 begins at block 102 by collecting prestack reflection data in the time domain from a seismic survey. The prestack reflection data may be collected by distributing seismic sources and receivers over a chosen survey area of interest. The prestack reflection data may be obtained when the seismic sources transmit controlled time pulses of acoustic or elastic energy, which travel through a medium such as water or layers of rocks and are then reflected or refracted, diffracted, or scattered onto the receivers. The Laplace domain waveform inversion method 100 then proceeds to block 104.

[21] At block 104, the Laplace domain waveform inversion method 100 may transform the reflected wavefield collected in the time domain to reflection data in the Laplace domain. The Laplace transform of a time domain wavefield $u(t)$ is defined as

$$u(s) = \int_0^{\infty} u(t) e^{-st} dt$$

[22]

[23] equation (1)

[24] where S is a real Laplace damping constant, and t is an instance in time. The product $u(t)e^{-st}$ in equation (1) may represent a damped time domain wavefield at a given Laplace

damping constant, s .

- [25] Furthermore, the Laplace transformed wavefield $u(s)$ may represent the zero or near zero frequency component of the Fourier transform of the time domain damped wavefield by introducing a complex frequency

$$u(s, \omega) = \lim_{\omega \rightarrow 0} \int_{-\infty}^{\infty} U(s, t) e^{-i\omega t} dt \cong \int_{-\infty}^{\infty} U(s, t) dt$$

[26]

- [27] equation (2)

- [28] Where, ω is the complex frequency, $U(s, t) = u(t) e^{-st}$ is the time domain damped wavefield.

- [29] FIG. 2A illustrates an embodiment of an undamped time domain wavefield 200. The time domain wavefield 200 that represents the prestack reflection data may contain multiple sharp peaks (and dips), which correspond to reflections from multiple layers under the surface. Damping the time domain wavefield 200 using a damping constant may reduce the number of visible peaks (and dips) in the wavefield, wherein the peaks (and dips) that correspond to later instances of time may be more heavily damped than those that correspond to earlier instances of time. As a result, the tail portion of the wavefield, or alternatively the latter peaks (and dips), may be significantly attenuated or even totally eliminated. The degree of attenuation of the latter peaks (and dips), as well as the extent of time over which they remain visible, may be dependent on the size of the damping constant. FIG. 2B illustrates an embodiment of a damped wavefield 202 obtained by damping the initially undamped wavefield 200 of FIG. 2A, using a relatively small damping constant ($s = 0.25$). For such a weakly damped wavefield 202, a considerable number of peaks (and dips) may remain visible at the earlier instances of time. FIG. 2C illustrates another damped wavefield 204 obtained by damping the wavefield 200 using a much larger damping constant ($s = 10$). In such case, the damping constant is sufficiently large so that the damped wavefield 204 may appear like a delta wave train where its peak amplitude resides at the first arrival instance of time, estimated around 1 second. Signal

noises in advance of the first arrival event of the wavefield may be muted before transforming the time domain reflected wavefield to reflection data in the Laplace domain. After transforming the time domain reflected wavefield to reflection data in the Laplace domain, the method 100 proceeds to block 106.

[30] At block 106, the Laplace domain waveform inversion method 100 may initialize an estimated velocity model that is assumed to resemble, in general properties at least if not in shape, the velocity model of the true collected wavefield data. The initial velocity model may be estimated using two-dimensional or three-dimensional wave velocity models, and by making some assumptions about the subsurface structure. The method 100 then progresses to block 108.

[31] At block 108, the Laplace domain waveform inversion method 100 may calculate the Laplace wavefield that corresponds to the initial estimated velocity model. The wavefield in the time domain may be calculated using the wave equation

$$[32] \quad \mathbf{M}\ddot{\mathbf{u}} + \mathbf{K}\mathbf{u} = \mathbf{f}$$

[33] equation (3)

[34] where $\mathbf{M}$ is a mass matrix, $\mathbf{K}$ is a stiffness matrix, $\mathbf{u}$ is a wavefield in the time domain, $\ddot{\mathbf{u}}$ is the second-order time derivative of $\mathbf{u}$, and $\mathbf{f}$ is a source vector. In order to calculate however the wavefield in the Laplace domain, a hybrid Laplace and Fourier transform of equation (3) with proper boundary conditions may be considered instead

$$[35] \quad \mathbf{S}\tilde{\mathbf{u}} = \tilde{\mathbf{f}}$$

[36] equation (4)

[37] where $\mathbf{S} = -\mathbf{M}\omega^2 + \mathbf{K}$, $\tilde{\mathbf{u}} = \int_0^{\infty} \mathbf{u}(t) e^{-i\omega t} dt$, $\tilde{\mathbf{f}} = \int_0^{\infty} \mathbf{f}(t) e^{-i\omega t} dt$, and ω is a complex frequency that may be expressed as

$$[38] \quad \omega = \omega_{\text{saml}}^* - is$$

[39] equation (5)

[40] where ω_{saml}^* may be less than $1/T_{\text{max}}$, wherein T_{max} is a maximum observed record length in time, s is a positive damping constant, and i is equal to $\sqrt{-1}$. The Laplace

domain wavefield $\tilde{\mathbf{u}}$ may be a real valued Laplace domain wavefield or a complex valued Laplace domain wavefield. The real valued Laplace domain wavefield may be calculated by choosing ω_{saml}^* equal to zero. The complex valued Laplace domain wavefield may be calculated by choosing ω_{saml}^* equal to a constant value and choosing s appropriately. In an embodiment, the Laplace domain wavefield $\tilde{\mathbf{u}}$ may be solved by a method comprising first factoring the matrix S , and second using a simple forward or backward substitution to obtain $\tilde{\mathbf{u}}$ in the Laplace domain. The Laplace domain wavefield $\tilde{\mathbf{u}}$ may also be solved by other methods known to persons of ordinary skill in the art. If the Laplace damping constant s is set to zero, then the Laplace domain wave equation (4) may be considered a Poisson's equation, which is known to provide smooth inversion results. Once a Laplace domain wavefield is calculated, the method 100 proceeds to block 110.

- [41] At block 110, the method 100 may calculate a logarithmic, integral, or power objective function. The solution of the wave equation in the Laplace domain may be equivalent to the integration of the damped wavefield for a given Laplace damping constant. The wavefield in the Laplace domain may be so small that the waveform inversion using a logarithmic, integral or power wavefield may be most effective. Hence, an objective function may be considered that is based on the exponent ratio of the estimated wavefield in the Laplace domain, $\tilde{\mathbf{u}}$, to the true wavefield in the Laplace domain, $\tilde{\mathbf{d}}$

$$E_{\text{logarithm}} = \sum_{s=1}^{N_{\text{freq}}} \sum_{i=1}^{N_{\text{src}}} \sum_{j=1}^{N_{\text{rcv}}} \left\{ \ln(\tilde{u}_{ij}(s)) - \ln(\tilde{d}_{ij}(s)) \right\}^2 = \sum_{s=1}^{N_{\text{freq}}} \sum_{i=1}^{N_{\text{src}}} \sum_{j=1}^{N_{\text{rcv}}} \left\{ \ln \left(\frac{\tilde{u}_{ij}(s)}{\tilde{d}_{ij}(s)} \right) \right\}^2,$$

$$E_{\text{integral}} = \sum_{s=1}^{N_{\text{freq}}} \sum_{i=1}^{N_{\text{src}}} \sum_{j=1}^{N_{\text{rcv}}} \left\{ \int_{p_1}^{p_2} \tilde{u}_{ij}(s)^p dp - \int_{p_1}^{p_2} \tilde{d}_{ij}(s)^p dp \right\}^2,$$

$$E_{\text{power}} = \sum_{s=1}^{N_{\text{freq}}} \sum_{i=1}^{N_{\text{src}}} \sum_{j=1}^{N_{\text{rcv}}} \left\{ \tilde{u}_{ij}(s)^p - \tilde{d}_{ij}(s)^p \right\}^2,$$

[42]

[43] equation (6)

[44] where N_{freq} is the number of Laplace damping constants considered, N_{src} and N_{rcv} is

the number of seismic receivers and seismic sources used to collect the wavefield data, respectively, and p may vary from 0 to 1 and may be bounded by P_1 and P_2 , where $P_2 > P_1$. The logarithmic, integral, or power objective function expressed in equation (6) may represent the summed squares (or squares of absolute values of complex wavefield) of all differences between the logarithmic, integral or power values of the Laplace estimated wavefield and the Laplace true wavefield, which may be collected from all sources and receivers.

[45] At block 112, the Laplace domain waveform inversion method 100 may examine the logarithmic, integral, or power objective function to verify if a convergence criterion of the objective function value is met. In an embodiment, the convergence criterion may be met if the logarithmic, integral, or power value is found equal to zero or below a certain minimum that may be considered negligible. In another embodiment, the convergence criterion may be met if the value of the logarithmic, integral, or power objective function at the final iteration of the method 100 may be equal or within a negligible distance in value to the logarithmic, integral, or power objective function obtained in the preceding iteration. If the convergence criterion is not satisfied, then the method 100 proceeds to block 114, otherwise the method 100 proceeds to block 116.

[46] At block 114, the method 100 may update the estimated velocity model by adding an adjusting value to the previously estimated velocity model of a prior iteration. In an embodiment, the adjusting value may be obtained by the steepest-descent method or the Gauss-Newton method. The steepest-descent method may resolve the adjusting values of the velocity model by seeking to minimize the logarithmic, integral, or power objective function. Minimizing the logarithmic, integral, or power objective function may be accomplished by solving for the velocity model value that renders the derivative value of the logarithmic, integral, or power objective equal to zero. The adjusting value may also be obtained by other optimization methods known to persons of ordinary skill in the art. After updating the estimated velocity model value, the method 100 proceeds to block 108.

where a new Laplace domain wavefield may be calculated and then used to recalculate the logarithmic, integral, or power objective function. The recalculated objective function may again be checked against the convergence criterion to determine whether or not the method 100 may exit the loop.

[47] At block 116 of method 100, the subsurface image may be generated using the final updated velocity model that meets the convergence criterion of the objective function. When the logarithmic, integral, or power objective function converges to a minimum, the final updated velocity model may be identical or sufficiently close to the true velocity model, which corresponds to the true collected Laplace domain wavefield data. Hence, the accurately estimated velocity model may be used with prestack depth migration models, known to persons of ordinary skill in the art, to reconstruct realistic subsurface images.

[48] In order for the waveform inversion to be successful with real data, a smooth and long wavelength velocity model should be recovered, which may be difficult to attain with conventional time domain or frequency domain waveform inversion. Retrieving the long wavelength velocity model may be a challenge due to exponentially increasing noise in lower frequency components of real collected seismic data. As shown above, the wave equation in the Laplace domain of equation (4) may be equivalent to a Poisson's equation. Hence, the waveform inversion in the Laplace domain may resemble the inversion of Poisson's equation, which provides smooth inversion results. The wavefield in the Laplace domain may also be closely associated with the velocity distribution, where a wavefield damped with a small Laplace constant may contain information of deep parts of the velocity model. In contrast, a wavefield damped with a large Laplace constant may show distinct responses at shallow parts of the velocity model. Since, the small Laplace damping constant may enable resolving a long wavelength velocity model for deep regions, the Laplace constant should be properly chosen in the waveform inversion of the Laplace domain.

[49] As shown in equation (1), the Laplace transform of a time domain wavefield may be

numerically calculated by integrating the damped wavefield in the limit of maximum recording time, using some numerical integration scheme, such as a trapezoidal integration technique. However, since the true analytic Laplace transform is an integration of the damped wavefield to the infinite time, a discrepancy or an integration error may be encountered between the analytic and the numerical integration. The amplitude of the damped wavefield at a large Laplace damping constant may be neglected for long recording time, where the integration error may be acceptable. In the case of a small Laplace damping constant, the amplitude of the damped wavefield may remain significant even for longer recording times. Hence, the error of the numerical integration at small Laplace damping constants to the finite maximum time may not be acceptable. Numerical tests of the Laplace transform for synthetic and real data may be made in order to choose an optimal lowest limit of the Laplace damping constant for waveform inversion. A Laplace damping constant substantially about zero is found to be the lowest tolerated limit that may result in negligible integration errors. In other embodiments, other constants may be used. The present disclosure is not limited to method 100 and blocks 102-116, and these steps or processes may be performed in the order provided in method 100, or in a different order. In some embodiments, the method might further include initializing a preliminary wavelet and updating a source wavelet. Also in other embodiments, various blocks 102-116 may be omitted or combined with other steps or processes known to those skilled in the art, all of which is within the scope of the present disclosure.

- [50] FIG. 3 illustrates an embodiment of objective functions in the frequency domain, 302 and 304, and objective functions in the Laplace domain, 306 and 308. All objective functions are generated for a 2D velocity profile A-A' of the SEG/EAGE 3D Salt model, where varying wavefields with velocities from 3 kilometer per second (km/s) to 6 km/s are calculated in both the frequency domain and the Laplace domain. The objective functions in the figure represent the summed squares of the logarithmic differences in values between the true Laplace domain wavefield and the Laplace domain wavefield

corresponding to varied velocities. A plurality of local minimum points on both sides of the global minimum point may be observed for the objective function 302 in the frequency domain at 7.5Hz. The objective function 304 at 4Hz, on the other hand, appears smoother with a smaller number of local minimum points, compared with that at 7.5 Hz. Unlike the objective functions in the frequency domain, the global minimum point at 4.45 km/s may be located for the objective function 306 with a 0.166 Laplace damping constant and for the objective function 308 with a 2.062 Laplace damping constant. Both objective functions have a similar hyperbolic shape characterized by the absence of local minimum points. Similar observations may also be made for objective functions of other velocity models in the Laplace domain. As a result of the smooth behavior and the absence of local minima in the Laplace domain objective functions, the waveform inversion in the Laplace domain may be more robust, when compared with that of the frequency domain. Because of the well-shaped behavior of the objective function in the Laplace domain the resolved results from the inversion may converge even if an initial model may be far from the true model.

- [51] FIG. 4 illustrates a typical, general-purpose computer system suitable for implementing one or more embodiments disclosed herein, such as but not limited to method 100 described above. The computer system 480 includes a processor 482 (which may be referred to as a central processor unit or CPU) that is in communication with memory devices including secondary storage 484, read only memory (ROM) 486, random access memory (RAM) 488, input/output (I/O) devices 490, and network connectivity devices 492. The processor may be implemented as one or more CPU chips.
- [52] The secondary storage 484 is typically comprised of one or more disk drives or tape drives and is used for non-volatile storage of data and as an over-flow data storage device if RAM 488 is not large enough to hold all working data. Secondary storage 484 may be used to store programs which are loaded into RAM 488 when such programs are selected for execution. The ROM 486 is used to store instructions and perhaps data which are

read during program execution. ROM 486 is a non-volatile memory device which typically has a small memory capacity relative to the larger memory capacity of secondary storage. The RAM 488 is used to store volatile data and perhaps to store instructions. Access to both ROM 486 and RAM 488 is typically faster than to secondary storage 484.

- [53] I/O devices 490 may include printers, video monitors, liquid crystal displays (LCDs), touch screen displays, keyboards, keypads, switches, dials, mice, track balls, voice recognizers, card readers, paper tape readers, or other well-known input devices.
- [54] The network connectivity devices 492 may take the form of modems, modem banks, ethernet cards, universal serial bus (USB) interface cards, serial interfaces, token ring cards, fiber distributed data interface (FDDI) cards, wireless local area network (WLAN) cards, radio transceiver cards such as code division multiple access (CDMA) and/or global system for mobile communications (GSM) radio transceiver cards, and other well-known network devices. These network connectivity devices 492 may enable the processor 482 to communicate with an Internet or one or more intranets. With such a network connection, it is contemplated that the processor 482 might receive information from the network, or might output information to the network in the course of performing the above-described method steps. Such information, which is often represented as a sequence of instructions to be executed using processor 482, may be received from and outputted to the network, for example, in the form of a computer data signal embodied in a carrier wave
- [55] Such information, which may include data or instructions to be executed using processor 482 for example, may be received from and outputted to the network, for example, in the form of a computer data baseband signal or signal embodied in a carrier wave. The baseband signal or signal embodied in the carrier wave generated by the network connectivity devices 492 may propagate in or on the surface of electrical conductors, in coaxial cables, in waveguides, in optical media, for example optical fiber, or in the air or free space. The information contained in the baseband signal or signal embedded in the

carrier wave may be ordered according to different sequences, as may be desirable for either processing or generating the information or transmitting or receiving the information. The baseband signal or signal embedded in the carrier wave, or other types of signals currently used or hereafter developed, referred to herein as the transmission medium, may be generated according to several methods well known to one skilled in the art.

- [56] The processor 482 executes instructions, codes, computer programs, scripts which it accesses from hard disk, floppy disk, optical disk (these various disk based systems may all be considered secondary storage 484), ROM 486, RAM 488, or the network connectivity devices 492.
- [57] While several embodiments have been provided in the present disclosure, it should be understood that the disclosed systems and methods might be embodied in many other specific forms without departing from the spirit or scope of the present disclosure. The present examples are to be considered as illustrative and not restrictive, and the intention is not to be limited to the details given herein. For example, the various elements or components may be combined or integrated in another system or certain features may be omitted, or not implemented.
- [58] In addition, techniques, systems, subsystems, and methods described and illustrated in the various embodiments as discrete or separate may be combined or integrated with other systems, modules, techniques, or methods without departing from the scope of the present disclosure. Other items shown or discussed as coupled or directly coupled or communicating with each other may be indirectly coupled or communicating through some interface, device, or intermediate component whether electrically, mechanically, or otherwise. Other examples of changes, substitutions, and alterations are ascertainable by one skilled in the art and could be made without departing from the spirit and scope disclosed herein.
- [59] Hereinafter, a subsurface structure imaging device based on Laplace domain waveform

inversion according to an embodiment of the present invention will be described according to the principle described above.

- [60] FIG. 5 illustrates the overall configuration of the subsurface structure imaging device based on Laplace domain waveform inversion, to which the above-described principle is applied.
- [61] In FIG. 5, the subsurface structure imaging device according to the embodiment of the present invention includes a seismic source 501, a plurality of receivers 502, a data processing unit 503, and a display unit 504.
- [62] The seismic source 501 is a device for generating predetermined wavelets to be transmitted to a survey target area 505. That is, generally, the seismic source 501 generates wavelets for a predetermined time and the receivers 502 measures data at predetermined time interval and length and obtains data through iteration.
- [63] Each of the receivers 502 is a device for receiving wavefield signals reflected from the subsurface of the survey target area 505. The plurality of receivers is installed at predetermined regular intervals. Sound detectors, sound sensors, geophones, and accelerometers, which detect sound waves, can be used as the receivers 502.
- [64] The data processing unit 503 is a device for receiving the wavefield signals, measured by the plurality of receiver 502, and generating image data used to image the subsurface structure of the survey target area 505 by processing the received wavefield using a predetermined method according to the embodiment of the present invention. A computer, a microprocessor, and a Field Programmable Gate Array (FPGA) can be used as the data processing unit 503.
- [65] The display unit 504 is a device for displaying the image data, and preferably displaying the distribution of subsurface mediums or geological subsurface images of the survey target area 505 using different colors.
- [66] FIG. 6 shows the data processing unit 503 in detail. As shown in the drawing, the data processing unit 503 includes a first input unit 601, a transform unit 602, a second input

unit 603, a parameter storage unit 604, a modeling wavefield generation unit 605, and a control unit 608.

- [67] The first input unit 601 performs a function of receiving wavefield $d(t)$ in a time domain from the receivers 502. Generally, a plurality of receivers 502 is installed, in which case the first input unit 601 collects a plurality of wavefield signals and generates the wavefield $d(t)$.
- [68] The transform unit 602 performs a function of receiving the wavefield $d(t)$ from the first input unit 601 and transforming it into wavefield $d(s)$ in a Laplace domain. Here, the transform unit 602 preferably uses one or more Laplace damping constants of 0 to 50.
- [69] The second input unit 603 performs a function of receiving a parameter which reflects the physical characteristics of the survey target area 505 from a user. In order to understand the actual physical characteristics of the survey target area 505, a predetermined modeling wavefield is generated using the parameter, the generated modeling wavefield is compared with actual measured data, and then the parameter must be updated such that the difference between the generated modeling wavefield and the actual measured data is minimized. Therefore, an initially estimated value is used as the parameter received through the second input unit 603.
- [70] Further, the parameter preferably includes information about the seismic source and information about the velocity and density of the subsurface. Here, the information about the seismic source indicates the waveform of the seismic source (that is, the amplitude and phase for each frequency of each seismic source), and the information about the velocity and density of the subsurface indicates the velocity model or the velocity/density model of the survey target area 505.
- [71] The parameter storage unit 604 performs a function of storing the parameter, and a general-purpose memory device can be used as the parameter storage unit 604. Since the parameter can be modified later, the parameter stored in the parameter storage unit 604 is renewed by being updated and is then stored.

- [72] *The modeling wavefield generation unit 605 generates modeling wavefield $u(s)$ about the survey target area in the Laplace domain using the parameter stored in the parameter storage unit 604.
- [73] The control unit 608 performs a function of receiving the wavefield $d(s)$ from the transform unit 602 and the modeling wavefield $u(s)$ from the modeling wavefield generation unit 605, and determining whether an difference between the wavefield $d(s)$ and the modeling wavefield $u(s)$ falls within a preset reference range.
- [74] Further, the control unit 608 performs a function of determining the difference, loading the parameter stored in the parameter storage unit 604 and generating image data if the difference falls within the reference range, and resetting, that is, updating the parameter stored in the parameter storage unit 604 if the difference does not fall within the reference range.
- [75] Here, for the reference range, the difference between the wavefield $d(s)$ and the modeling wavefield $u(s)$ preferably falls within the range of $\pm 1\%$ to 30%. In other words, preferably, if the difference falls within the range of $\pm 1\%$ to 30%, the image data is generated, and, if the difference does not fall within the range of $\pm 1\%$ to 30%, the parameter is updated.
- [76] For this purpose, the control unit 608 may include a comparison unit 610, an objective function generation unit 606, a parameter reset unit 607, and an image data generation unit 609.
- [77] The objective function generation unit 606 performs a function of generating an objective function 'E' which indicates the degree of difference between the wavefield $d(s)$ and the modeling wavefield $u(s)$.
- [78] The objective function 'E' is used to define the difference between the wavefield $d(s)$ and the modeling wavefield $u(s)$, and for details thereof, reference can be made to above-described block 110.

- [79] The comparison unit 610 performs a function of determining whether the objective function 'E' calculated by the objective function generation unit 606, falls within the preset reference range.
- [80] The parameter reset unit 607 performs a function of updating the parameter stored in the parameter storage unit 604 if the range of the difference between the wavefield $d(s)$ and the modeling wavefield $u(s)$ does not fall within the reference range. Here, preferably, the increment of the parameter is obtained by calculating a gradient for the objective function 'E' generated by the objective function generation unit 606, so that the parameter is updated.
- [81] If the range of the difference between the wavefield $d(s)$ and the modeling wavefield $u(s)$ falls within the reference range, the image data generation unit 609 performs a function of loading the parameter stored in the parameter storage unit 604 at this time, and generating image data.
- [82] For example, in the case in which the parameter indicates the distribution of the velocity of the wavefield, the image data generation unit 609 can generate image data through a subsurface structure imaging process (migration process) using the obtained velocity of the subsurface and the time domain data $d(t)$, and apply the image data to the display unit 504.

Claims

- [1] A Laplace transform system comprising:
a processor;
a measured time domain wavefield;
a velocity model; and
Laplace damping constants, wherein the processor is programmed to calculate a substantially about zero frequency component of a Fourier transform of a time domain damped wavefield, wherein the time domain damped wavefield is damped by the Laplace damping constants to obtain long wavelength velocity information for deeper subsurface regions.
- [2] The system of claim 1 wherein a Laplace transform of the measured time domain wavefield is equivalent to a Poisson's equation when the Laplace damping constant is equal to zero.
- [3] The system of claim 1 wherein the measured time domain wavefield is measured using seismic sources and receivers on a surface of a geological site of interest.
- [4] The system of claim 1 wherein the measured time domain wavefield is prestack reflection data from subsurface structure.
- [5] The system of claim 1 wherein a Laplace transform of the measured time domain wavefield is numerically calculated by integrating the damped time domain wavefield in a limit of a maximum recording time.
- [6] The system of claim 1 wherein optimum values from 0 to 100 are chosen for the Laplace damping constant of the measured time domain wavefield to minimize integration error.
- [7] The system of claim 1 wherein a small Laplace damping constant is used in a Laplace transform of the measured time domain wavefield to obtain information of deep parts of the waveform velocity model.
- [8] The system of claim 1 wherein a large Laplace damping constant is used in a Laplace transform of the measured time domain wavefield to resolve information of shallow parts

of the waveform velocity model.

- [9] A Laplace domain inversion system comprising:
a processor;
a damped recorded wavefield in a Laplace domain;
a wave equation;
an objective function; and
a velocity model, wherein the processor is programmed to solve the wave equation in the Laplace domain, minimize the objective function, and calculate the velocity model that corresponds to the damped recorded wavefield to analyze subsurface regions.
- [10] The system of claim 9 further comprising a source wavelet, wherein the processor is programmed to calculate the source wavelet and the velocity model.
- [11] The system of claim 9 wherein the objective function is one of a logarithmic, an integral, and a power function.
- [12] The system of claim 9 wherein the damped recorded wavefield in a Laplace domain is converted from data in a time domain.
- [13] The system of claim 9 wherein the wave equation in a time domain comprises a wavefield component, a second-order time derivative of the wavefield component, a mass matrix component, and a stiffness matrix component.
- [14] The system of claim 9 wherein the wave equation with proper boundary conditions, and using one of a real Laplace damping constant, and a complex Laplace damping constant, is solved in the Laplace domain by a factorization of some components of the wave equation and using forward or backward mathematical substitutions to obtain a damped calculated wavefield.
- [15] The system of claim 9 wherein the objective function is equal to a summed squares of all differences between one of logarithmic, integral or power values of the damped recorded wavefield and a calculated damped wavefield.
- [16] The system of claim 9 wherein the objective function is smooth and comprises no local

minima or a small number of local minima.

- [17] The system of claim 9 wherein one of a steepest-descent method, and a Gauss-Newton method is used to minimize the objective function by solving for a velocity model value that reduces a derivative value of the logarithmic objective to zero.
- [18] The system of claim 9 wherein the processor is programmed to iterate starting with an initially calculated damped wavefield.
- [19] The system of claim 9 wherein the processor is programmed to converge to the velocity model that corresponds to the damped recorded wavefield even if a different damped wavefield is initially calculated.
- [20] A method for analyzing subsurface regions, comprising:
 - receiving collected prestack reflection data in a time domain;
 - transforming the time domain prestack reflection data to Laplace domain reflection data;
 - initializing a preliminary velocity model that represents a subsurface structure;
 - calculating one of a logarithmic, an integral, and a power objective function;
 - verifying whether the objective function satisfies a convergence criterion;
 - updating the velocity model if the convergence criterion is not met; and
 - generating a subsurface image from the velocity model if the convergence criterion is met to analyze subsurface regions.
- [21] The method of claim 20 further comprising:
 - using both the transformed prestack reflection data in the Laplace domain and the updated velocity model to minimize one of the logarithmic, the integral, and the power objective function in an iterative manner until the convergence criterion is met.
- [22] The method of claim 21 further comprising:
 - initializing a preliminary source wavelet; and
 - updating the source wavelet.
- [23] The method of claim 20 further comprising:
 - confirming that the convergence criterion is met when the value of one of the logarithmic,

the integral, and the power objective function at a final iteration is found below a certain minimum and with a negligible difference from the values of the preceding iterations.

[24] The method of claim 20 further comprising generating a subsurface image from the final updated velocity model using prestack depth migration models.

[25] A subsurface structure imaging device based on Laplace domain waveform inversion, the subsurface structure imaging device comprising:

one or more receivers for receiving wavefield signals from a survey target area; and

a data processing unit for processing the wavefield signals in order to generate image data, so that a subsurface structure of the survey target area is imaged, wherein the data processing unit comprises:

a first input unit for receiving a wavefield $d(t)$ in a time domain from the receivers;

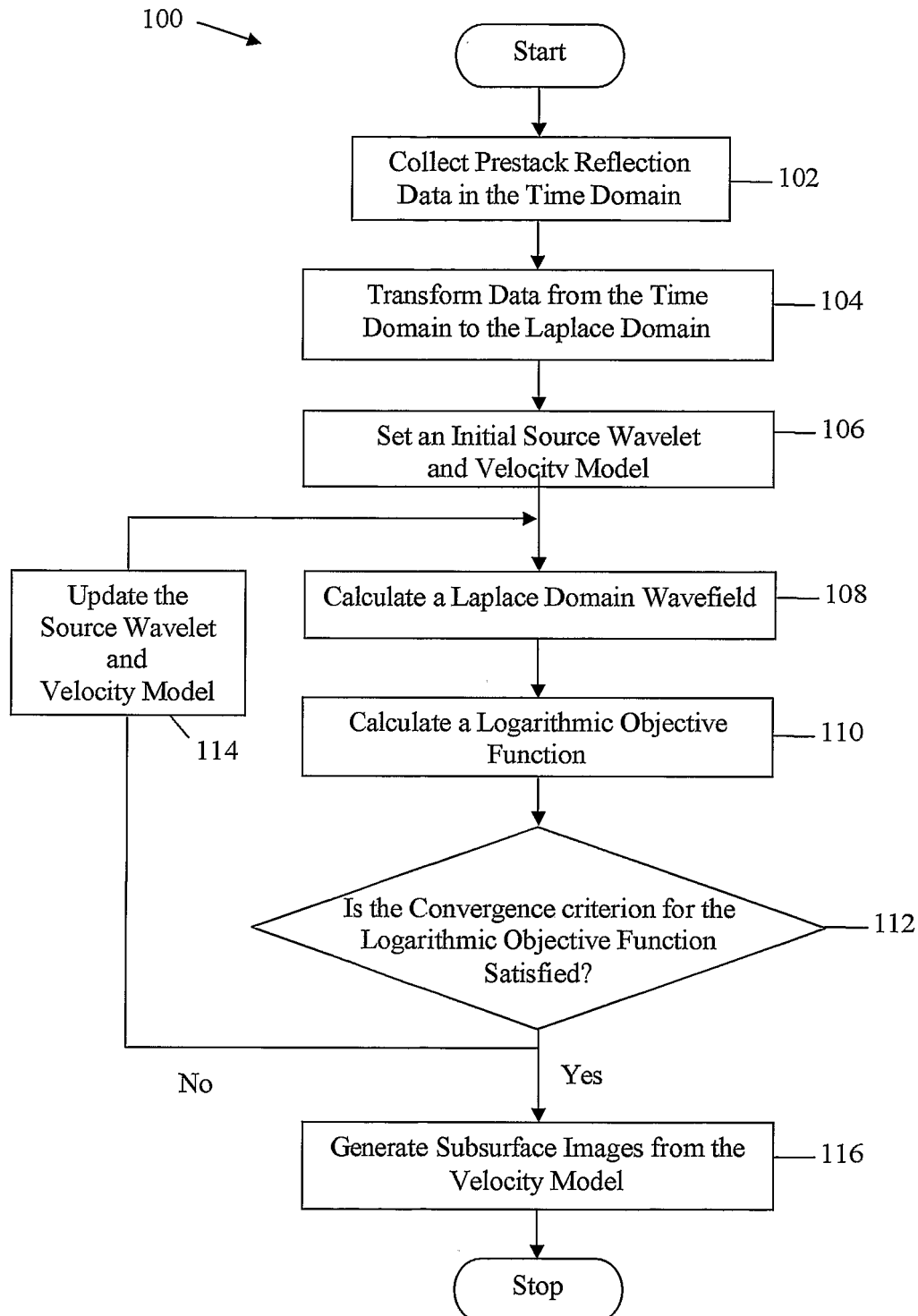
a transform unit for receiving the wavefield $d(t)$ from the first input unit and transforming it into a wavefield $d(s)$ in a Laplace domain;

a parameter storage unit for storing one or more parameters that reflect physical characteristics of the survey target area;

a modeling wavefield generation unit for receiving one of the parameters stored in the parameter storage unit and generating a modeling wavefield $u(s)$ in the Laplace domain; and

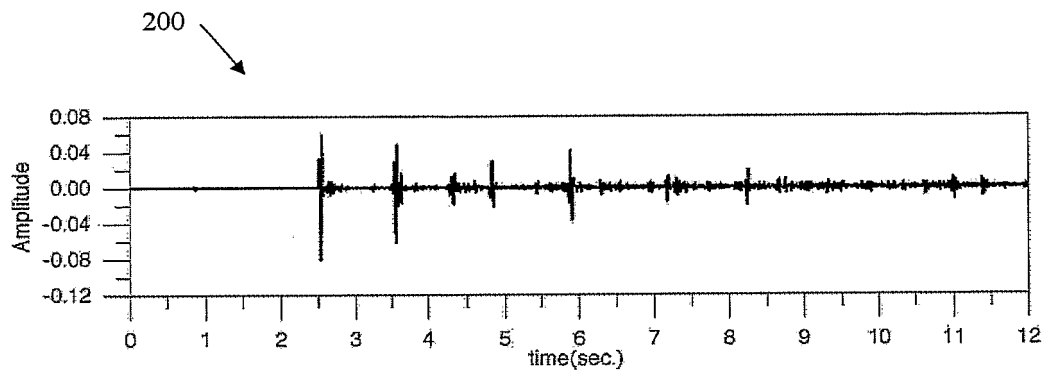
a control unit for receiving the wavefield $d(s)$ from the transform unit and the modeling wavefield $u(s)$ from the modeling wavefield generation unit, determining whether a difference between the wavefield $d(s)$ and the modeling wavefield $u(s)$ falls within a preset reference range, generating image data using one of the parameters stored in the parameter storage unit in advance if the difference falls within the reference range, and resetting the parameter stored in the parameter storage unit in advance if the difference does not fall within the reference range.

[Fig. 1]

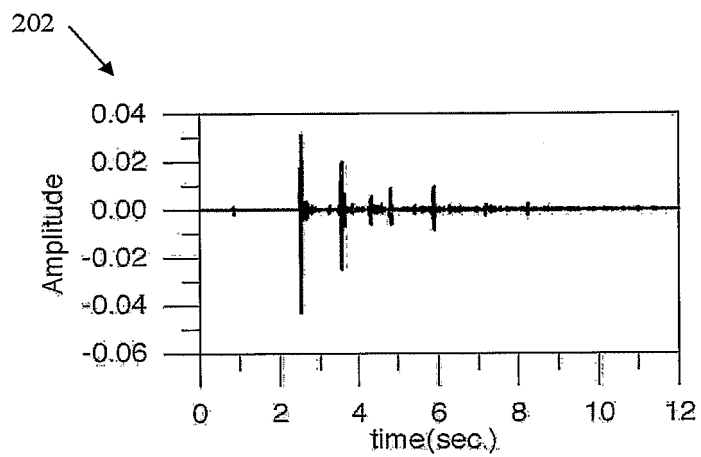


[Fig. 2]

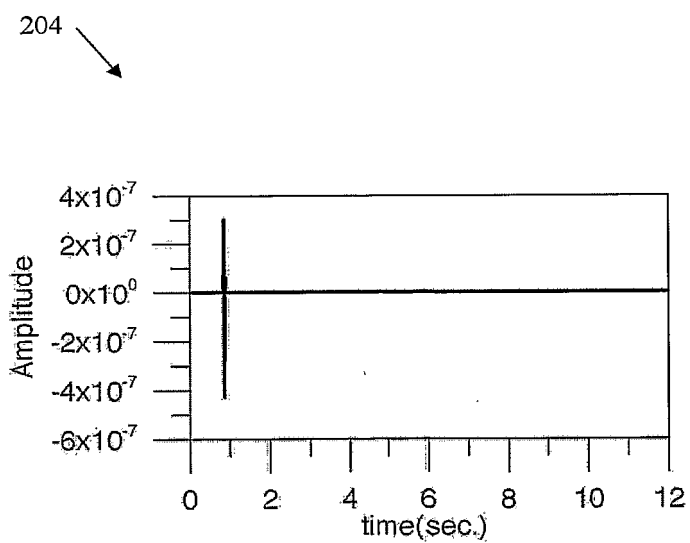
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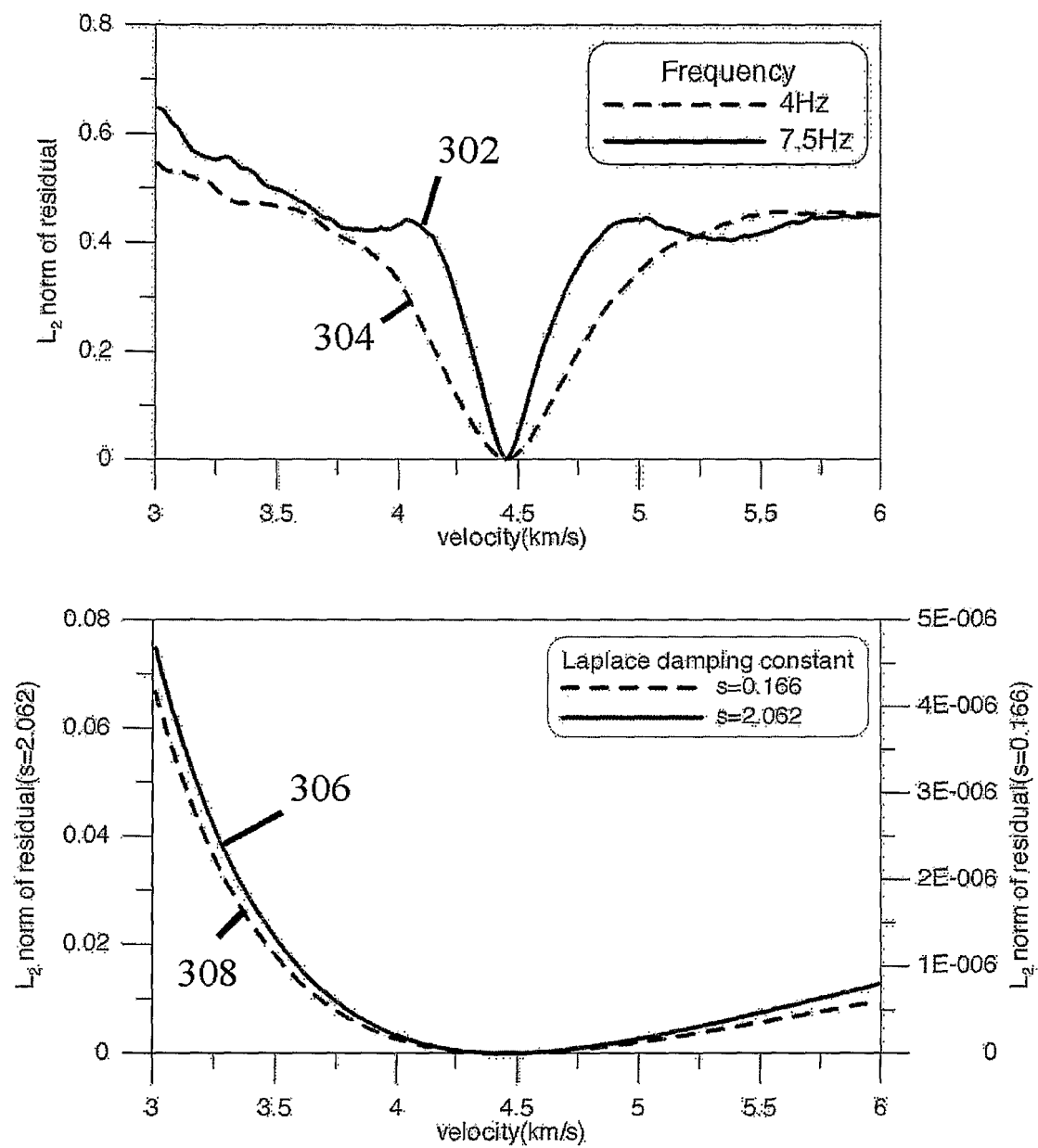
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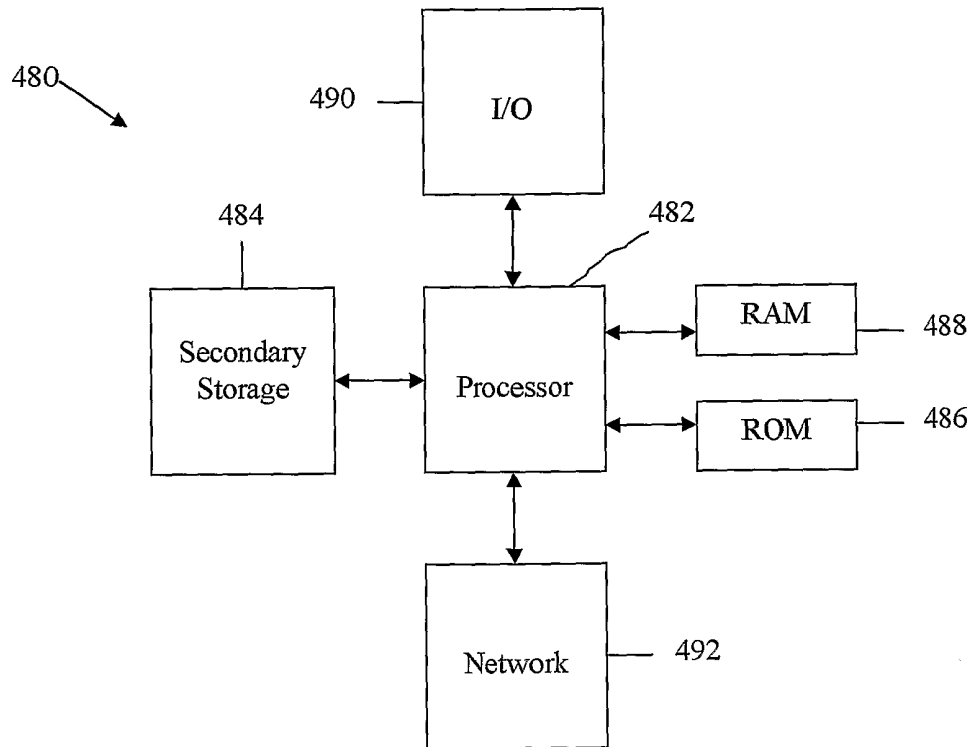
c



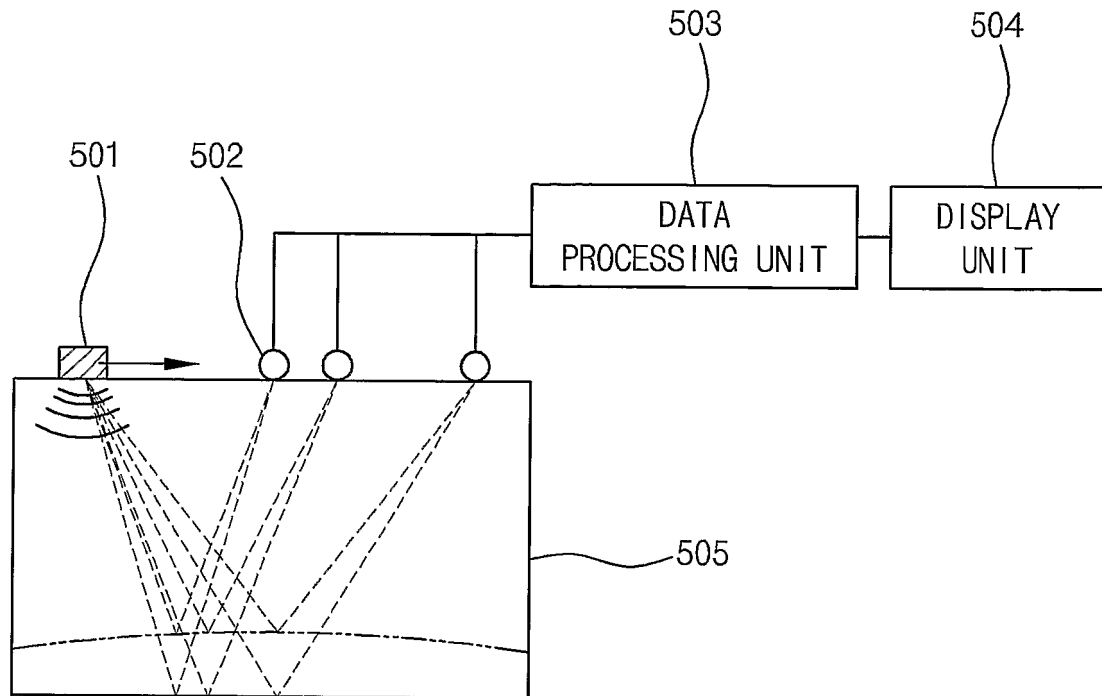
[Fig. 3]



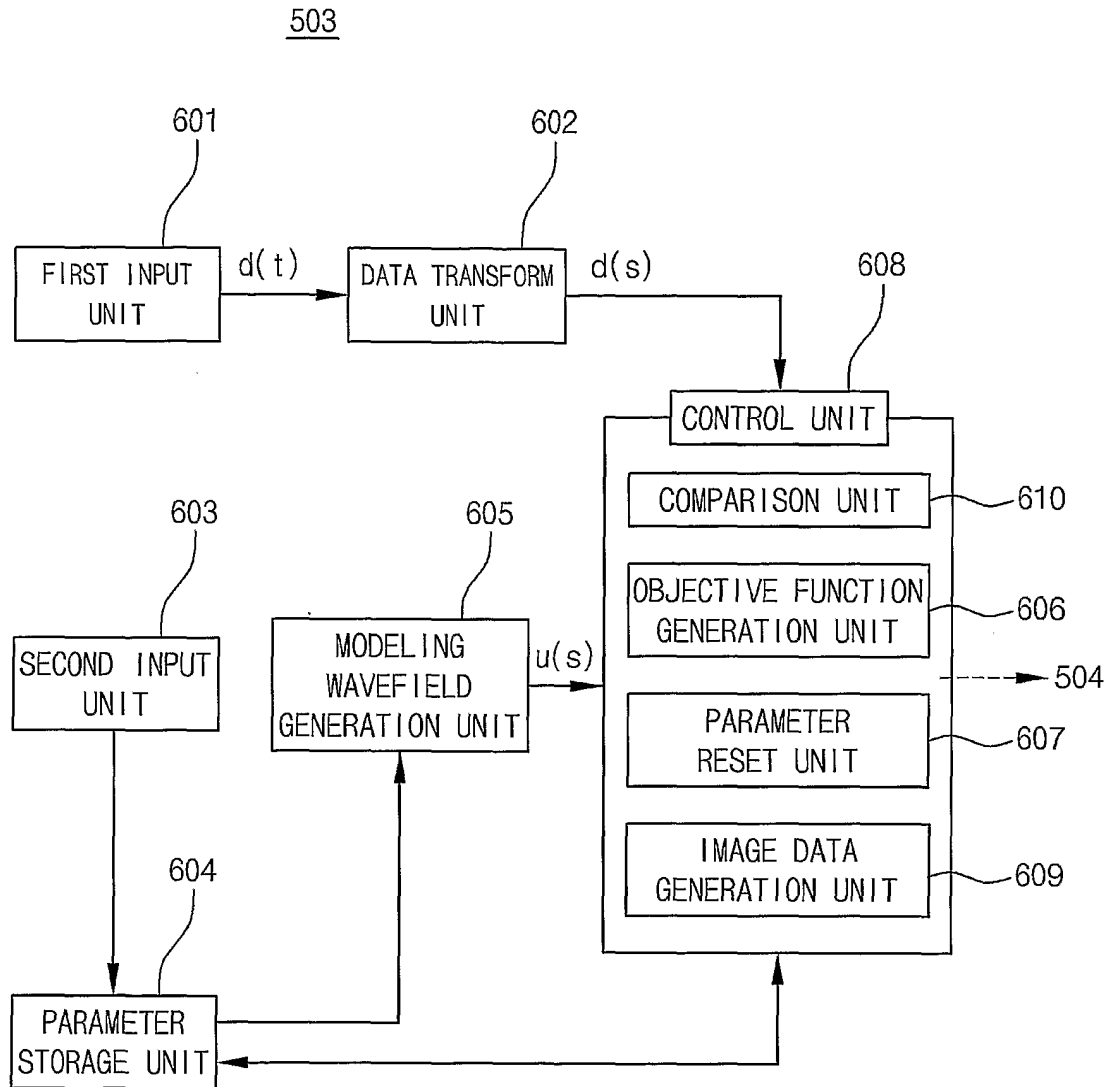
[Fig. 4]



[Fig. 5]



[Fig. 6]



INTERNATIONAL SEARCH REPORT

International application No.
PCT/KR2008/000792**A. CLASSIFICATION OF SUBJECT MATTER****G01V 3/08(2006.01)i, G06F 17/14(2006.01)i**

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)

IPC 8 G01V 3/08

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

Korean utility models and applications for utility models since 1975
Japanese utility models and applications for utility models since 1975

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

eKIPASS (KIPO internal) "Laplace transform", "wavefield", "time"

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	Kim et al. '3-D seismic imaging using high-performance parallel direct solver for large-scale finite element analysis.' : In High-Performance Computing in Asia-Pacific Region, 2005. Proceedings. Eighth International Conference. IEEE, 2005. See figs. 1-5, abstract and introduction	9-24
A		1-8, 25
A	R. Gerhard Pratt, Seismic waveform inversion in the frequency domain, Part 1: Theory and verification in a physical scale model. GEOPHYSICS, May 1999, Vol. 64, pages 888-901. See abstract and pages 888-892	1-25
A	Van de Sype et al. Small-signal z-domain analysis of digitally controlled converters. IEEE Transactions on power electronics, March 2006, Vol. 21, pages 470-478. See the whole document	1-25

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

* Special categories of cited documents:

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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

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search

29 MAY 2008 (29.05.2008)

Date of mailing of the international search report

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