DEVICE AND METHOD FOR IMAGING OF NON-LINEAR AND LINEAR PROPERTIES OF FORMATIONS SURROUNDING A BOREHOLE

GOVERNMENT RIGHTS

[0001] This invention was made with Government support under Cooperative Research and Development Agreement (***CRADA***) Contract Number DE-AC52-06NA25396 awarded by the United States Department of Energy. The Government may have certain rights in this invention.

FIELD

[0002] The present disclosure relates generally to acoustic interrogation of rock formations around a borehole and more particularly to imaging of non-linear and linear properties of formation surrounding the borehole.

BACKGROUND

[0003] Detailed characterization of natural and induced fractures away from the borehole, reliable sequestration of CO_2, assessing mechanical integrity and predicting borehole breakout in oil and gas reservoirs, and probing cement integrity require new approaches to material characterization and imaging. Among the existing probes of material elasticity, the elastic nonlinear response (anelasticity) is an approach to probe material integrity. The elastic nonlinearity of a solid is a measure of the material mechanical damage state. Elastic nonlinear response tends to be the best measure of material damage. Thus, as a near-borehole probe, nonlinear methods hold the most promise for discerning mechanically damaged regions or potential crack/fracture conduits.

SUMMARY

[0004] In accordance with ~~an~~some aspects of the present disclosure, a method for investigating material surrounding a borehole is disclosed. The method includes generating a first lower frequency acoustic wave within the borehole, wherein the first lower frequency acoustic wave induces a linear and a nonlinear response in one or more features in the material that are substantially perpendicular to a radius of the borehole; directing a

first sequence of higher frequency pulses in a ~~perpendicular~~ direction perpendicular with respect to the longitudinal axis of the borehole into the material contemporaneously with the first acoustic wave; and receiving one or more second higher frequency pulses at one or more receivers positionable in the borehole produced by an interaction between the first sequence of higher frequency pulses and the one or more features undergoing linear and nonlinear elastic distortion due to the first lower frequency acoustic wave ~~order~~ to investigate the material surrounding the borehole.

[0005] In the method, the second high frequency pulses can be received at the one or more receivers if the first sequence of high frequency pulses encounters the one or more features within the material with a contrast in acoustic impedance that results in reflection or backscattering of energy to the borehole. In the method, the second high frequency pulses can be received at the one or more receivers if the first sequence of high frequency pulses encounters the one or more features that are oriented such that the one or more features directs energy back to the borehole while undergoing the distortion due to the first low frequency acoustic wave such that the distortion alters the contrast in the acoustic impedance during a cycle of the low frequency acoustic wave.

[0006] In the method, the first acoustic wave and the first sequence of high frequency pulses can be generated by a compressional wave source and/or a shear wave source. In the case that the first acoustic wave is from a shear wave source, one or more features in the material may experience crack shearing that will imprint a signature on the high frequency reflected pulses. In the case that the first acoustic wave is from a compressional wave source and the first sequence of high frequency pulses are shear waves the receivers will tend to receive reflected energy during the pump induced crack dilation in the one or more features. In some embodiment ~~aspects~~, the source of the first acoustic wave can include a vibrating member that is configured to induce elastic nonlinearity in the material.

[0007] In the method, the one or more receivers can be arranged in an array in the borehole and can be configured to record one or more directional components of the one or more second high frequency pulses.

[0008] The method can include repeating the generating the first acoustic wave and the directing with the first sequence of high frequency pulses directed at different azimuth orientations and at different depths within the borehole to produce three-dimensional

images of linear and nonlinear reflecting and backscattering features of the material surrounding the borehole. The material surrounding the borehole can include cement, casing, rock formations, fluids in or surrounding the borehole, disbonds in the cement/rock interface and/or the steel casing/cement interface. The received second high frequency pulses can have properties that depend on a phase of the low frequency wave at a location and a time at which the first sequence of high frequency pulses are reflected by the material.

[0009] The method can further include determining whether the material includes a linear reflector or a nonlinear reflector based on the received one or more second high frequency pulses. The method can also further include filtering the received one or more second high frequency pulses. The filter can include a high pass filter that can isolate high frequency components from the received one or more second high frequency pulses. Moreover, the method can include determining an amplitude change over time of the filtered one or more second high frequency pulses. The first sequence of high frequency pulses can be either chirped or coded or both chirped and coded. The first sequence of high frequency pulses can be modulated in amplitude, phase, and/or period.

[0010] In some embodiment~~aspect~~s, the first sequence of high frequency pulses can have a frequency between about 10 to 1000 times that of the low frequency acoustic wave.

[0011] In some embodiment~~aspect~~s, the method can include determining a radial distance to the one or more features using a first time, the time at which the first sequence of high frequency pulses were transmitted, and a second time, the time at which the second high frequency pulses were received, and an estimated velocity of sound of the material surrounding the borehole. The determination can include computing a cross-correlation of the first sequence of high frequency pulses and second high frequency pulses.

[0012] In some embodiment~~aspect~~s, the second high frequency pulses can be received at the one or more receivers if the first sequence of high frequency pulses encounters a nonlinear elastic feature in the material that is oriented such that feature directs energy back while undergoing crack shearing.

[0013] In accordance with an aspect of the present disclosur~~e~~e, an apparatus for investigating material surrounding a borehole is disclosed. The apparatus includes a first acoustic wave source, positionable in the borehole, configured to generate a first acoustic wave, having a

lower frequency into the material, that induces a linear and a nonlinear response in one or more features in the material that are substantially parallel to a longitudinal axis of the borehole. The apparatus includes a source positionable in the borehole and configured to direct a first sequence of higher frequency pulses in a direction perpendicular to the longitudinal axis of the borehole into the material contemporaneously with the first acoustic wave. The apparatus includes one or more receivers positionable in the borehole and configured to receive one or more second higher frequency pulses produced by an interaction between the first sequence of higher frequency pulses and the one or more features~~material~~ undergoing linear and nonlinear elastic distortion due to the first acoustic wave~~.~~ to investigate the material surrounding the borehole.

[0014] In some embodiment~~aspects~~, the second high frequency pulses can be received at the one or more receivers if the first sequence of high frequency pulses encounters the one or more features within the material with a contrast in acoustic impedance that results in reflection or backscattering of energy to the borehole. Moreover, the second high frequency pulses can be received at the one or more receivers if the first sequence of high frequency pulses encounters the one or more features that are oriented such that the one or more features directs energy back to the borehole while undergoing the distortion due to the first low frequency acoustic wave such that the distortion alters the contrast in the acoustic impedance during a cycle of the low frequency acoustic wave.

[0015] In some embodiment~~aspects~~, the first acoustic wave source, the source of the first sequence of high frequency pulses or both can be configured to produce a compressional wave, a shear wave or both. The first acoustic wave source can include a vibrating member that is configured to induce elastic nonlinearity in the material.

[0016] In some embodiment~~aspects~~, the one or more receivers can be arranged in an array in the borehole. Moreover, the one or more receivers can be configured to record one or more directional components of the one or more second high frequency pulses.

[0017] In some embodiment~~aspects~~, the apparatus can include a processor in communication with a memory having instructions which permit determination of a radial distance to the one or more features from the borehole. The apparatus can include a processor in communication with a memory having instructions which permit the construction of one or more three-dimensional images of the material based on repeated acoustic wave penetrations into the material at different azimuth orientations and at different depths within the borehole. The

material surrounding the borehole can include cement, casing, rock formations, fluids in or surrounding the borehole, and/or disbonds in the cement/rock interface and/or the casing/cement interface. Further, the apparatus can include a processor in communication with a memory having machine executable instructions stored therein which, when executed cause the processor to determine the presence in the material of linear reflectors and/or a nonlinear reflectors based on the received one or more second high frequency pulses.

[0018] In some embodimentaspects, the apparatus can include a filter that is arranged to filter the received one or more second high frequency pulses. The filter can include a high pass filter that is arranged to isolate the high frequency components of the received one or more second high frequency pulses. In some aspects, the apparatus includes a processor that can be configured to determine the amplitude change over time of the filtered one or more second high frequency pulses.

[0019] In some embodimentaspects, the apparatus can include an encoder arranged to encode the first sequence of high frequency pulses with a time-varying signature by introducing chirps and/or frequency protocols. In some aspects, the apparatus includes a processor that can use the encoded first sequence of high frequency pulses to measure a time-of-flight between the first sequence of high frequency pulses and the received second high frequency pulses. The time-varying signature can include a change with time in an amplitude, a phase, and/or a period of the first sequence of high frequency pulses.

[0020] In some embodimentaspects, the first sequence of high frequency pulses have a frequency between about 10 to 1000 times that of the low frequency acoustic wave.

[0021] In some embodimentaspects, the radial distance is determined by computing a cross-correlation in a time domain with the first and the second sequences of high frequency pulses. The processor can be arranged to determine the radial distance to the material based upon a first time at which the first sequence of high frequency pulses were transmitted, a second time at which the second sequence of high frequency pulses where received and an estimated velocity of sound of the material.

[0022] In accordance with anothersome aspects of the present disclosure, a method for investigating material surrounding a borehole is disclosed. The method includes generating within a borehole an intermittent lower frequency vibration that propagates as a

tube wave longitudinally to the borehole and induces a nonlinear response in one or more features in the material that are substantially perpendicular to a longitudinal axis of the borehole; generating within the borehole a sequence of high frequency pulses directed such that they travel longitudinally to the borehole within the surrounding material; and receiving, at one or more receivers positionable in the borehole, a signal that includes components from the lower frequency vibration and the sequence of higher frequency pulses during intermittent generation of the lower frequency vibration, to investigate the material surrounding the borehole.

[0023] In some embodiment~~aspect~~s, the sequence of high frequency pulses can be configured to propagate into the material as refracted waves, scattered waves or direct waves. In the method, the low frequency vibration, the sequence of high frequency pulses or both can be produced by a compressional source, a shear wave source or both wherein the compressional source, the shear wave source or both can include a vibrating member that is configured to induce elastic nonlinearity into the material.

[0024] In some embodiment~~aspect~~s, the one or more receivers can be arranged in an array in the borehole and the one or more receivers can be configured to record one or more directional components of the sequence of high frequency pulses.

[0025] The method can include repeating the generating the low frequency vibration and the sequences of high frequency pulses at different azimuth orientations and at different depths within the borehole to produce one or more images of the material or properties of the material including a linear velocity, a linear modulus, a nonlinear velocity and/or a nonlinear modulus.

[0026] In some embodiment~~aspect~~s, an elastic distortion cycle can be caused by the low frequency vibration results in a corresponding cyclical variation in local velocity in the material.

[0027] In some embodiment~~aspect~~s, the method can include processing a sequence of high frequencies pulses returned to the one or more receivers from the material to determine an elastic nonlinear response of the material.

[0028] In accordance with an~~some~~ aspects of the present disclosure, an apparatus for investigating material surrounding a borehole is disclosed. The apparatus can include a first acoustic wave source configured to generate within a borehole an intermittent lower frequency vibration that propagates as a tube wave longitudinally to the borehole and

induces a nonlinear response in one or more features in the material that are substantially perpendicular to a longitudinal axis of the borehole; a second acoustic wave source configured to direct a continuous sequence of higher frequency pulses longitudinally to the borehole into the material; and one or more receivers positionable in the borehole and configured to receive a signal that includes components from the lower frequency vibration and the sequence of higher frequency pulses during intermittent generation of the lower frequency vibration, to investigate the material surrounding the borehole.

[0029] In some embodimentaspects, the sequence of high frequency pulses can be configured to propagate into the material as refracted waves, scattered waves or direct waves. In some embodimentaspects, the first acoustic wave source, the second acoustic wave source, or both can include a compressional source, a shear wave source or both, wherein the compressional source, the shear wave source or both can include a vibrating member that is configured to induce elastic nonlinearity into the material.

[0030] In some embodimentaspects, the one or more receivers can be arranged in an array in the borehole and can be configured to record one or more directional components of the sequence of high frequency pulses.

[0031] In some embodimentaspects, the apparatus can include a controller configured to repeat the generation of the low frequency vibration and the sequences of high frequency pulses at different azimuth orientations and at different depths within the borehole to produce one or more images of the material or properties of the material including a linear velocity, a linear modulus, a nonlinear velocity and/or a nonlinear modulus.

[0032] In some embodimentaspects, an elastic distortion cycle of the low frequency vibration generated by the first acoustic wave source can result in a corresponding cyclical variation in local velocity in the material.

[0033] In some embodimentaspects, the apparatus can include a processor in communication with a memory having machine executable instructions stored therein which, when executed cause the processor to determine an elastic nonlinear response of the material based on a sequence of high frequencies pulses returned to the one or more receivers from the material.

[0034] These and other objects, features, and characteristics of the present invention, as well as the methods of operation and functions of the related elements of structure and the

CLAIMS

1. A method for investigating material surrounding a borehole, the method comprising:

generating a first lower frequency acoustic wave within the borehole, wherein the first lower frequency acoustic wave induces a linear and a nonlinear response in one or more features in the material that are substantially perpendicular to a radius of the borehole;

directing a first sequence of higher frequency pulses in a direction perpendicular with respect to the longitudinal axis of the borehole into the material contemporaneously with the first acoustic wave; and

receiving one or more second higher frequency pulses at one or more receivers positionable in the borehole produced by an interaction between the first sequence of higher frequency pulses and the one or more features undergoing linear and nonlinear elastic distortion due to the first ~~low~~ lower frequency acoustic wave to investigate the material surrounding the borehole.

2. The method according to claim 1, wherein the second higher frequency pulses are received at the one or more receivers if the first sequence of higher frequency pulses encounters the one or more features within the material with a contrast in acoustic impedance resulting in reflection or backscattering of energy to the borehole.

3. The method according to claim 2, wherein the second higher frequency pulses are received at the one or more receivers if the first sequence of higher frequency pulses encounters the one or more features that is oriented such that the one or more feature directs energy back to the borehole while undergoing the distortion due to the first ~~low~~ lower frequency acoustic wave such that the distortion alters the contrast in the acoustic impedance during a cycle of the ~~low~~ first lower frequency acoustic wave.

4. The method according to claim 1, wherein the first acoustic wave and the first sequence of higher frequency pulses are generated by a compressional wave source, a shear wave source or both.

5. The method according to claim 4, wherein a source of the first acoustic wave includes a vibrating member that is configured to induce the linear and nonlinear elastic distortions in the material.

6. The method according to claim 1, wherein the one or more receivers are arranged in an array in the borehole.

7. The method according to claim 1, wherein the one or more receivers are configured to record one or more directional components of the one or more second higher frequency pulses.

8. The method according to claim 1, further comprising repeating the generating the first acoustic wave and the directing the first sequence of higher frequency pulses at different azimuth orientations and at different depths within the borehole to produce three-dimensional images of linear and nonlinear elastic features of the material surrounding the borehole.

9. The method according to claim 1, wherein the material surrounding the borehole is selected from the group consisting of: cement, casing, rock formations, fluids in or surrounding the borehole and combinations thereof.

10. The method according to claim 1, wherein the received second higher frequency pulses has properties that depend on a phase of the ~~low~~ first lower frequency wave at a location and a time at which the first sequence of higher frequency pulses are reflected by the material.

11. The method according to claim 1, further comprising determining whether the material includes a linear reflector or a nonlinear reflector based on the received one or more second higher frequency pulses.

12. The method according to claim 11, further comprising filtering the received one or more second higher frequency pulses.

13. The method according to claim 12, wherein the filter includes a high pass filter that is arranged to isolate higher frequency components from the received one or more second higher frequency pulses.

14. The method according to claim 11, further comprising determining an amplitude change with time of the filtered one or more second higher frequency pulses.

15. The method according to claim 1, wherein the first sequence of higher frequency pulses are either chirped or coded or both chirped and coded.

16. The method according to claim 1, wherein the first sequence of higher frequency pulses is modulated, and the modulation is selected from the group consisting of: amplitude, phase, period and any combination thereof.

17. The method according to claim 1, wherein between five and 100 first frequency pulses are emitted per cycle of the ~~low~~ first lower frequency wave, and the first higher frequency pulses have a frequency at least ten times a frequency of the ~~low~~ first lower frequency wave .

18. The method according to claim 1, further comprising determining a radial distance to the one or more features based upon a first time at which the first sequence of higher frequency pulses were transmitted, a second time at which the second sequence of higher frequency pulses where received and an estimated velocity of sound along the path of the first sequence of higher frequency pulses and along the path of the second higher frequency pulses.

19. The method according to claim 18, wherein the determining includes computing a cross-correlation of the first sequence of higher frequency pulses and the second higher frequency pulses. .

20. The method according to claim 1, wherein the second higher frequency pulses are received at the one or more receivers if the first sequence of higher frequency pulses encounters