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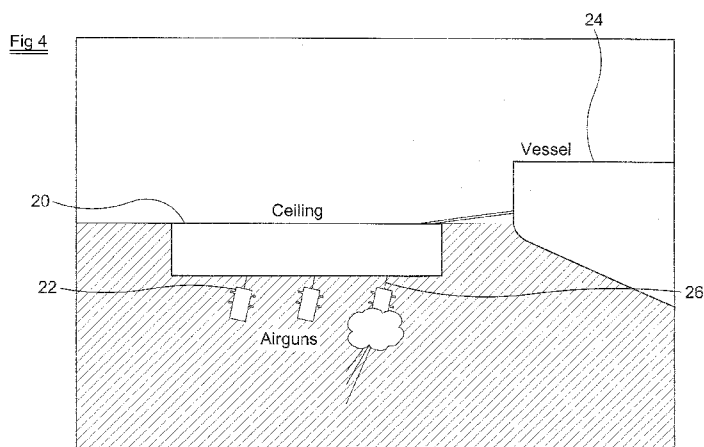
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(54) Title: IMPROVED SEISMIC SOURCES AND METHODS OF CONDUCTING A SEISMIC SURVEY



(57) Abstract: A marine seismic source arrangement for conducting a seismic survey of a solid geological formation below water, comprises: at least one acoustic source for emitting an acoustic wave in said water, and a solid acoustic ceiling positioned in use above said acoustic source; wherein said acoustic ceiling: a) has a positive effective reflection coefficient so that down going components of said acoustic wave vertically below the source interfere constructively with components of said acoustic wave reflected from said ceiling; and b) is arranged to float on the surface of said water during use.

IMPROVED SEISMIC SOURCES AND METHODS OF CONDUCTING A SEISMIC SURVEY

Field of the invention

The invention relates to the field of seismic surveys, and particularly marine seismic surveys.

Background of the invention

A marine seismic exploration survey with the objective to map hydrocarbon deposits within geological formations typically involves deploying one or several seismic sources beneath the sea surface and seismic sensors at predetermined locations as illustrated in Figure 1. Figure 1 shows a marine seismic survey 2 in which a vessel 4 tows a source 6 and a streamer 8. The source 6 may comprise one or more air guns 10. The streamer comprises one or more seismic sensors, which may be hydrophones. Both the source 6 and the streamer 8 are towed beneath the surface of the water 14.

The sources generate seismic waves which propagate into the geological formations 12 below the water 14. Changes in elastic properties of the geological formations 12 reflect, refract and scatter the seismic waves, changing their direction of propagation. Part of the reflected energy reaches the seismic sensors which can be hydrophones sensitive to pressure changes and/or geophones sensitive to particle motion. Analysis of the seismic data can then indicate the presence or absence of probable locations of hydrocarbon accumulations.

A seismic source is defined as any device which releases energy into the earth in the form of seismic waves. The major type in marine exploration is air-gun array sources, which since the 1970's have been by far the most popular ones. The air-gun can be described as a chamber with compressed air that is released to the surrounding water through port(s) to create an acoustic pulse. The main reasons for their popularity are that their pulses are predictable, repeatable and controllable, and that they use compressed air which is cheap and readily available.

Another type of source is the water gun. In the following, the discussion will refer to air guns, although the principles we discuss are not limited to air guns.

The time domain pressure pulse that is emitted by an air gun in the downwards direction is called the primary pulse. However, air guns produce unwanted pulses commonly called "source ghost" pulses and "bubble" pulses. These pulses produce unwanted components in the seismic signal that is transmitted into the subsurface of the geological formation (12).

The source ghost pulse is the signal which travels upward from the source, is reflected down at the sea surface and joins the original, primary downward-travelling pressure pulse from the source. From a seismic data processing point of view, the source ghost is often considered to be an intrinsic feature of the source wavefield, and therefore often included in the definition of the source signature.

The physics of the source ghost in relation to marine sources is illustrated in Figure 2. The upward travelling part of the source signal cannot escape into the air. The sea surface acts as a mirror, and it reflects the signal downwards with opposite polarity. This source ghost pulse is delayed in time with respect to the initially downgoing primary pulse from the source. Geometrically, the source ghost appears to originate from the mirror image of the seismic source. The time delay of the ghost pulse is given by

$$\tau = 2d \cos\theta / c \quad (1)$$

where d is the source depth, c is the sound of speed in water, and θ is the offset angle of the initial downgoing primary pulse measured from the vertical axis.

We assume that the initially downgoing pulse has amplitude $A=1/2$. In the frequency domain, the effect of the ghost then is to modify the initial pulse by the so-called ghost factor

$$G(f) = (1/2)(1 + r_0 \exp(2\pi f d \cos\theta / c)) \quad (2)$$

where f is frequency and the reflection coefficient $r_0=-1$ for a free surface with vanishing pressure (i.e. the air above the water). Because of the effectively zero pressure at the

sea surface the ghost pulse gets the opposite polarity in relation to the initial pulse. The frequency spectrum of the ghost factor then is

$$|G(f)| = \sin(2\pi f d \cos\theta / c) \quad (3)$$

The spectrum has zeroes called 'ghost notches' at frequencies

$$f_n = ncl(ld \cos\theta) \quad (4)$$

where n is zero or positive integer. The first notch ($n=0$) is always at $f_0=0$ Hz. This is a strong contributing reason to the fact that in seismic data acquisition we can lose the low frequency components in relation to noise. The useful frequency band of seismic data is between the first and the second zeroes in the amplitude spectrum of the source signature (inside f_0 and f_1). The existence of zeroes in the spectrum, caused by the source ghost and therefore called ghost notches, implies that there is no signal, but only noise, at these particular frequencies. As the offset angle increases, the ghost notch frequency increases. The inability to use low frequencies as a result of the first notch is particularly problematic when exploring regions containing basalt volcanic rock and salt layers. In order to effectively "see through" basalt and salt layers it is necessary to use low frequencies, for example in the range 1 to 10 Hz. Frequencies in the range 0 Hz to 40 Hz may also be desirable for this purpose. However the ghost notch at zero frequency results in low signal strengths at low frequencies, and this is a particular problem when it is necessary to use low frequencies to "see through" basalt and salt layers.

The ghost notches are seen to result from the interference between the primary downgoing pulse and the secondary ghost pulse. The phase differences between the two pulses causes attenuation and enhancement of spectral component within the bandwidth of the source signature. Attenuation is most severe at the frequencies where the pulses are 180 degrees out of phase. Enhancement is most significant at the frequencies where the pulses are in phase.

Since the source ghost effect depends on source depth the gun depth is an important parameter in source and survey design. In Figure 3 we display the effect the source

ghost has on the amplitude spectrum of the source signature in the vertical direction ($\theta=0$) for source depths of 3.75 m, 7.5 m and 15 m.

If high-resolution seismic of the shallow subsurface is the objective, it is important to extend the high-frequencies as much as possible. For a source at a depth of 3.75 m, the second ghost notch is at frequency $f_1=200$ Hz, but the low-frequency amplitudes are much lower than for a source depth of, for example, 15 m. As low frequencies improve penetration into the subsurface, a shallow source is not recommended for a deep-looking survey. By comparison, a 15 m source depth has nice low-frequency characteristics for good penetration, but the ghost notch at $f_1=50$ Hz has a detrimental effect on resolution. A survey with both low-frequency and high-frequency objectives is difficult to realize. It can be seen from this that in conventional exploration the survey objective dictates the source depth.

An introduction to this area of seismology is provided in Ikelle, L. T. and Amundsen, L., 2005, Introduction to petroleum seismology: Society of Exploration Geophysics.

Air guns, which generate an acoustic wave by suddenly releasing compressed gas into the water, also generate bubble pulses. When the compressed gas is released, the pressure inside the bubble greatly exceeds the hydrostatic (external) pressure. The air bubble expands well beyond the point at which the internal and hydrostatic pressures are equal. When the expansion ceases, the internal bubble pressure is below the hydrostatic pressure, so that the bubble starts to collapse. The collapse overshoots the equilibrium position and the cycle starts once again. The bubble continues to oscillate, with a period typically in the range of tens to hundreds of milliseconds. The oscillation is stopped due to frictional forces, and the buoyancy of the bubble causes it to break the sea surface.

The dominant frequency of the bubble oscillations decreases with increasing gun volume, or with increasing gun pressure, or with decreasing source depth. Therefore, small guns emit higher frequencies and big guns emit lower frequencies.

Use of a single air gun will result in a seismic signal whose frequency spectrum will exhibit a series of peaks and notches related to the bubble pulse oscillation period. To produce a seismic signal with a flatter frequency spectrum, it is common practice to

deploy a number of different air-guns in arrays. Guns with different volumes have different bubble periods, leading to a constructive summation of the first (primary) peak and destructive summation of the bubble amplitudes.

Summary of the invention

The invention provides a marine seismic source and a method of conducting a seismic survey as set out in the accompanying claims.

Brief description of the figures

Figure 1 shows a marine seismic survey;

Figure 2 shows the geometry of a primary pulse from a seismic source and a ghost pulse reflected from the sea surface;

Figure 3 shows the effect which the ghost pulse has on the amplitude spectrum of the source in the direction vertically downwards, for 3 different source depths of 3.75m, 7.5m and 15m;

Figure 4 is a schematic diagram showing a ceiling at the surface of the water and above a seismic source, in the form of an array of air guns;

Figure 5 is a schematic diagram showing a ceiling below the surface of the water and above a seismic source, in the form of an array of air guns;

Figure 6 is a schematic diagram in which an array of air guns is mounted to a ceiling at the surface of the water, with the air guns on the underside of the ceiling;

Figure 7 shows frequency spectra of a ghost factor for effective reflection coefficients from 0 to -1;

Figure 8 shows frequency spectra of a ghost factor for effective reflection coefficients from 0 to +1;

Figure 9 shows an acoustic ceiling in the water which has an upper part which is air-filled and a lower part which is high-impedance; and

Figure 10 shows the results of modelling the frequency responses of signals 200 m below the acoustic ceiling of Figure 9.

Description of preferred embodiments

Figure 4 shows an arrangement in which a ceiling structure 20 is positioned above an array of air guns 22. In this embodiment the ceiling floats on the surface of the water and is towed by a vessel 24. The air guns 22 are tethered to the ceiling 20 by means of connectors 26, which can be flexible cables.

Figure 5 shows a similar arrangement in which corresponding parts are given the same reference numerals. The difference in this embodiment is that the ceiling is positioned below the surface of the water, but still above the air guns 22.

Figure 6 shows a further embodiment, in which corresponding parts are again given the same reference numerals. However, in this embodiment the air guns 22 are firmly mounted to the underside of the ceiling 20.

In each of these embodiments the ceiling has an impedance that differs from the impedance of the sea water. The impedance can vary vertically and laterally. In contrast to the sea surface which has a reflection coefficient that is close to $r_0 = -1$, the ceiling has an effective reflection coefficient r which may vary vertically and laterally and may depend on frequency.

The ceiling has finite extent. The seismic source therefore should be deployed close to the device. The seismic source may emit an acoustic wave in the frequency range of for example 1Hz to 300Hz.

The ceiling, which is preferably a floating object in the sea, can take any suitable form. It is also possible to use a system including a number of such ceilings. In one realization of the ceiling, the ceiling can be a vessel that is autonomous or towed above

a seismic source. In another realization the ceiling is a man-made construction that can be towed above the seismic source.

A vessel may contain one or more layers. Any such layer may for example comprise air, water, a solid such as concrete, or a heavy liquid or semi-solid, e.g., mud, into which a gas such as air may have been mixed. In one embodiment the ceiling is a barge containing sand and/or gravel or a similar grained material, preferably at least partially saturated with air and/or water; such material may form one of a plurality of layers in the vessel. The barge or other ceiling may have dimensions of about 20 metres. For example, the length may be in the range 2 to 30 metres, e.g., 5m, and the width may be in the range 2 to 30 metres, e.g., 5m. Other dimensions are also possible. The width and length of the acoustic ceiling are preferably at least 3 metres or at least 5m or at least 10 meters. The impedance and the attenuation of the ceiling can be made high in order to attenuate the ghost pulse.

In the case where the ceiling comprises a vessel, barge or other floating container containing material, the underside of the vessel, barge or container is preferably continuous and/or smooth. The underside of the vessel, barge or container preferably does not distort much as a result of the acoustic wave, and is preferably structurally strong enough not to break or perforate as a result of operation of the acoustic source or by the acoustic wave. The underside of a vessel such as a barge may be formed of, for example, metal such as steel or aluminum, plastic, concrete or composite material such as fibreglass. In order to float on water the overall density of the acoustic ceiling (including any vessel or container) is preferably less than that of water, so that the acoustic ceiling is buoyant. Thus, in order to float, the vessel or container may for example contain light material, e.g. air, above a dense high impedance ceiling body.

The acoustic ceiling, or in the case of a vessel the material within the vessel, is preferably at least 0.5 meters thick, in order to ensure the necessary level of attenuation. Ideally it is at least 1 meter thick. Preferably, when the acoustic wave passes through the acoustic ceiling its amplitude on the far side of the ceiling is reduced to less than 75%, or 50%, compared to its initial amplitude when it first reaches the ceiling.

The effective reflection coefficient provided by the ceiling should be greater (i.e. more positive) than -1, which is the reflection coefficient of the water/air boundary. The effective reflection coefficient is preferably positive, so that constructive interference occurs at low frequencies, particularly in the range 1 to 10 Hz, thus increasing the signal strength at these frequencies, as shown in Figure 8. The higher the value of the effective reflection coefficient the better, and the value is preferably greater than 0.1 or, more preferably, greater than 0.5. Values greater than 0.9, and up to and including +1 are also possible. However, a compromise has to be found between the size and weight of the ceiling and the effective reflection coefficient. The effective reflection coefficient may also be frequency dependent, in which case the effective reflection coefficient should be positive, and may have the preferred values mentioned above, at least for a frequency in the range 1 to 10 Hz, preferably for all frequencies in this range, more preferably for all frequencies in a range from 0 Hz or 1 Hz to either 20 or 40 Hz; in embodiments, however, the lower frequency for each of these ranges may be 5 Hz instead of 0 or 1 Hz.

Preferably the source is positioned directly below the acoustic ceiling. In the case of an effective reflection coefficient of +1, constructive interference directly below the source occurs up to a frequency of $250/D$, where D is the distance between the source and the acoustic ceiling. The invention therefore preferably uses frequencies in the range from 0 to $250/D$. Specifically, the upper frequency limit, for example, up to a frequency point, F_0 , where the ghost interference does not produce a net magnitude change of the downgoing signal (though it may still make a phase change), which occurs at $F_0 = v/(6d)$, d =distance between source and interface, v =velocity in water approx 1500, i.e $F_0 = 250/d$. (i.e 10 Hz if $d=25m$, but higher if the d is smaller). The range may include frequencies up to 20 Hz or up to 40 Hz, for example, with frequencies between 10 and 15 Hz being particularly important.

We refer to the effective reflection coefficient because in practice there may be a number of reflections involved. Some of the energy of the ghost pulse may be reflected from the sea/air interface around the ceiling. Some of the energy of the ghost pulse may pass through the ceiling and be reflected at the ceiling/air boundary above the ceiling. The effective reflection coefficient of the ceiling is the reflection coefficient of the ceiling taking into account these factors.

The effect of the ceiling is to change the effective reflection properties of the sea surface. The method involves deploying one or several objects, here for brevity called the ceiling, on or below the sea surface, above one, several or all of the seismic sources.

The difficulties generated by the presence of a source ghost and bubbles can be remedied if the ceiling is configured to suppress the generation of the ghost pulse and bubbles.

To illustrate the impact and benefit of the ceiling in changing the reflection property of the sea surface, we display in Figures 7 and 8 frequency spectra of the ghost factor (see equation (2) above) for the special cases of constant reflection coefficients ranging from values $r=-1$ to $r=0$ and from $r=0$ to $r=1$, respectively. The case $r=0$ means that there is no reflection. We observe that as the reflection coefficient of the ceiling increases (i.e. becomes more positive) from $r=-1$, the amplitude of the ghost factor at low frequencies gets significantly larger. Furthermore, no notches are present in the frequency spectra.

Fig 9 shows an example of a ceiling which can have attenuation to decrease the ghost contribution (free surface contribution), in particular for low frequencies. In this case, the effective reflection coefficient of the ceiling may be frequency dependent.

Figure 9 shows an acoustic ceiling 30 in the water 32 which has an upper part 34 which is air-filled and a lower part 36 which is high-impedance with or without attenuation.

Impedance = density x seismic velocity. High impedance may refer to values that are higher than water impedance (ie about $1000\text{kg/m}^3 \times 1500\text{m/s} = 1\,500\,000\text{ kg/m}^2\text{s}$). The impedance of the lower part 36 is also typically less than $(10\,000\text{ kg/m}^3 \times 6000\text{ m/s}) = 60\,000\,000\text{ kg/m}^2\text{s}$.

The acoustic ceiling 30 is arranged above an acoustic source 38. The effective seismic property of the material between the upper and lower surface of the acoustic ceiling 30 represents either high impedance or high attenuation or both.

High attenuation is typically more than 0.5dB/m for a plane wave, where $\text{dB} = 20\log_{10}(A/A_0)$. A = amplitude at 1m along the propagation direction, A_0 = amplitude at 0m. 0.5dB/m attenuation means the amplitude is 0.5dB less at 1m compared to 0 m, i.e. -0.5dB reduction (assuming the plane wave propagates in the positive direction). That is, the amplitude at 1m compared to at 0 m: $A_1/A_0=10^{(-0.5/20)} = 0.9441$, i.e. about 5.6% reduction. The amplitude is preferably reduced by at least 5%. The attenuation may be frequency dependent, in which case these attenuation values preferably apply to at least one frequency (preferably all frequencies) in the frequency range of interest, for example in any one of the ranges 0 to 10 Hz, 0 to 20 Hz or 0 to 40 Hz, or any one of the ranges between 1 or 5Hz and any of 10, 20 or 40 Hz.

As mentioned above, the acoustic ceiling 30 may be high impedance, high attenuation or both. These combinations will now be discussed, with examples of the construction of the acoustic ceiling 30.

Four examples of an acoustic ceiling with high impedance and low attenuation are as follows:

- 1) Dense water saturated mud / drilling fluid (eg. including a large portion of the heavy rock forming mineral Barite, BaSO_4) with densities over 3000 kg/m³ (and seismic velocity between 1300 and 2000 m/s)
- 2) Homogenous solid, such as concrete (water saturated or dry) (density=2000 - 3000 kg /m³ , velocity= 4000-6000m/s).
- 3) Homogenous heavy and/or stiff metal, such as massive steel (density about 7000 kg/m³, velocity about 6000m/s).
- 4) Water saturated porous rock, sand, gravel or solid mix made up of fragments of blocks from 2) and 3) above, where the permeability is low (eg less than 0.1 Darcy).

Three examples of an acoustic ceiling with high impedance and high attenuation are as follows:

- 1) The same as 1) or 4) above, but saturated with a mix of water and air, i.e. partly water saturated.
- 2) Partly water saturated or fully water saturated assembly of blocks of concrete, rock or heavy metal (steel), where the average diameter of each block

element is more than 5 -10 cm, - ensuring high permeability(> 0.1 Darcy) for fluid flow.

- 3) A dense steel structure, assembled by steel bar elements, where the connection between each steel element is made up by damping springs.

In the case of an acoustic ceiling having high attenuation and low impedance, the impedance is preferably not lower than 500 000 kg/m²s.

By attenuation we mean the rate at which the acoustic signal is attenuated as it travels through the acoustic ceiling. When an acoustic wave arrives at the acoustic ceiling a primary reflection occurs at the boundary of the acoustic ceiling with the sea water. This reflection occurs as a result of a difference between the impedance of the sea water (Z1) and the impedance of the acoustic ceiling (Z2), where the reflection coefficient (for plane waves with normal incidence) is given by:

$$R = (Z2 - Z1) / (Z2 + Z1)$$

However some acoustic energy is transmitted through the acoustic ceiling and is reflected by the other side of the acoustic ceiling. A number of such reflections can occur, so that acoustic energy can bounce back and forth within the acoustic ceiling, with some of the energy being transmitted back into the water at each reflection. If the acoustic ceiling has a high attenuation then the effect of these "internal reverberations" is reduced. This is particularly important if the net effect of the internal reverberations is to transmit waves into the water which interfere destructively with the down-going signal from the source. It can therefore be seen that the combination of high impedance and high attenuation is particularly beneficial. The high impedance of the ceiling results in a positive reflection coefficient, so the primary reflection from the ceiling interferes constructively with the down-going signal from the source. At the same time high attenuation within the acoustic ceiling minimises the effect of internal reverberations within the ceiling which interfere destructively with the down-going source signal.

Generally, it is preferred that the impedance of the ceiling is higher than the impedance of the water.

The acoustic ceiling 30 can be, for example, a vessel hull containing, or filled with, heavy granular or blocky material, or a heavy structural skeleton, surrounded by a fluid (liquid and/or gas). In this embodiment the upper part of the ceiling 30 may be air-filled to provide the vessel with sufficient buoyancy, thus allowing it to float with the high impedance lower part 36. In this context heavy means a density of more than 2,000 kg/m³.

To enhance friction and attenuation inside the acoustic ceiling 30, in addition to the possible viscous attenuation created by a fluid, special materials like polymers can be added to the solid contact points of the blocky material, as described below.

The material structure or skeleton referred to above is built up of elements which have connection points / joints between each element, to bind the structure together. In our case we wish to damp the motion between the structural elements (which may be bars) at each joint. That is possible using damping materials in the joints acting as springs with dash-pots, for example normal vibration damping springs, or special damping materials such as polymer, like sorbothane

The acoustic ceiling 30 can be constructed in a layered manner, with different acoustic/elastic and attenuating properties in different layers.

Figure 10 shows the results of modelling the frequency responses (in the range 2-50 Hz) of signals 200 m below the acoustic ceiling 30 of Figure 9 in the two cases where the upper part 34 of the acoustic ceiling 30 is air-filled and the lower part 36 is high-impedance with or without attenuation. The source 38 is 2 m below the ceiling 30. For the sake of comparison, the response with no ceiling is included. The example illustrates the benefit of including a ceiling above the seismic source during surveying.

The model used was a 2D domain model, with the following parameters: 20m wide scatter object, 2m thick, density= 3000kg/m³, velocity=1500m/s, attenuation = 10dB/m (red curve), attenuation = 0dB(blue curve), source 2m below the lower boundary of the ceiling

The embodiments described change the effective reflectivity of the sea surface above a seismic source with the object of attenuating the source ghost reflection pulse and bubble oscillations.

The ceiling also has an improved effect on the bubble pulses. In addition to suppressing reflection of bubble pulses from the surface of the water, the ceiling has an effect on the bubbles themselves. The bubbles from an air gun rise upwards at a speed of about 1 meter per second. The bubbles continue to oscillate as they rise. For a gun depth of 7 metres the bubbles therefore oscillate for up to about 7 seconds. However the presence of the ceiling prevents the bubbles from rising, and causes the bubbles to break up. A particular advantage is obtained if the ceiling is relatively close to the air gun, such as in the case where the air gun is mounted to the ceiling, as in the embodiment of Figure 6 for example. The ceiling may for example be positioned no more than 1 meter above the air gun or guns.

Benefits of the proposed method include:

- More low frequencies will be available from the source, which are important for improved seismic imaging below complex overburden and seismic inversion.
- The effect of ghost notches will be significantly reduced, which will increase signal to noise ratio and enhance seismic resolution.
- The bubble effect may be reduced, giving source signatures with higher primary to bubble ratios.

The presence of a ceiling above an air gun is particularly beneficial in allowing low frequencies to be used, for example between 1 Hz and 10 Hz, as we have discussed above. This allows the system to see through basalt and salt layers. The seismic survey may also wish to use normal frequencies, for example in the range 10 - 120 Hz. It is therefore possible, in certain embodiments, to position a ceiling above only some of the air guns. These air guns can be used to collect data using low frequencies. At the same time other air guns can be used to collect data using normal frequencies. The air guns with and without ceilings can be timed appropriately so that they go off at different times. The air guns with and without ceilings may form part of the same air gun array, and be towed by the same vessel, and used to collect data in the same survey. In this way a more accurate model of the geological formations below the water can be produced.

In this specification where a value or range of values is specified for a property, such as reflection coefficient, impedance or attenuation for example, and where such a property has a frequency dependence, it should be understood that the value or range of values applies to the range of frequencies being used in the seismic survey, or to at least one frequency within that range. Suitable frequency ranges for such a seismic survey include any of the ranges 0-10, 0-20 or 0-40 Hz, or any range from 1 or 5 Hz to 10, 20 or 40Hz.

In addition to the embodiments and statements of invention referred to above, the invention may be defined by any of the following numbered paragraphs which correspond with the claims of the priority application:

1. A marine seismic source for use in conducting a seismic survey of a geological formation below water, said source comprising:

at least one acoustic source for emitting an acoustic wave in said water, and

an acoustic ceiling for positioning, in use, above said acoustic source so that a reflection of said acoustic wave from said ceiling is reduced in amplitude compared to reflection of said acoustic wave from a boundary between said water and air.

2. A marine seismic source as defined in paragraph 1, wherein said acoustic source is physically connected to said acoustic ceiling.

3. A marine seismic source as defined in paragraph 2, wherein said acoustic source is connected to said acoustic ceiling by a flexible cable.

4. A marine seismic source as defined in paragraph 2, wherein said acoustic source is connected to said acoustic ceiling in a rigid manner, so that said acoustic source and acoustic ceiling are substantially fixed in position relative to each other.

5. A marine seismic source as defined in any preceding paragraph, wherein said acoustic source is positioned beneath the surface of said water.

6. A marine seismic source as defined in any preceding paragraph, wherein said acoustic ceiling has a lower surface which is positioned beneath the surface of said water.
7. A marine seismic source as defined in paragraph 6, wherein said acoustic ceiling has an upper surface which is also positioned beneath the surface of said water.
8. A marine seismic source as defined in paragraph 6, wherein said acoustic ceiling is provided by the underside of a vessel.
9. A marine seismic source as defined in paragraph 8, wherein said vessel is a powered vessel which comprises power means for powering itself through said water.
10. A marine seismic source as defined in any preceding paragraph, wherein when placed in said water said acoustic ceiling has an effective reflection coefficient of greater than -0.9, that is more positive than -0.9.
11. A marine seismic source as defined in paragraph 10, wherein when placed in said water said acoustic ceiling has an effective reflection coefficient of greater than -0.7.
12. A marine seismic source as defined in paragraph 11, wherein when placed in said water said acoustic ceiling has an effective reflection coefficient of greater than -0.5.
13. A marine seismic source as defined in any of paragraphs 10 to 12, wherein when placed in said water said acoustic ceiling has an effective reflection coefficient between -0.9 and +0.9.
14. A marine seismic source as defined in any preceding paragraph, wherein said acoustic ceiling is positioned in the path of a ghost pulse, which is a pulse generated by said acoustic source which, in the absence of said acoustic ceiling, travels substantially parallel with a primary pulse from said acoustic source after reflection from the surface of said water.

15. A marine seismic source as defined in any preceding paragraph, wherein said at least one acoustic source is an array of acoustic sources.

16. A marine seismic source as defined in paragraph 15, wherein said array of acoustic sources comprises at least one acoustic source which produces a ghost pulse which has no acoustic ceiling positioned in the path of the ghost pulse.

17. A marine seismic source as defined in any preceding paragraph, wherein at least one of said acoustic sources produces an acoustic wave in the frequency range 1 Hz to 10 Hz.

18. A marine seismic source as defined in any preceding paragraphs, wherein at least one of said acoustic sources produces an acoustic wave in the frequency range 10 Hz to 120 Hz.

19. A marine seismic source as defined in any preceding paragraph, wherein at least one of said acoustic sources is an air gun.

20. A marine seismic source as defined in any of paragraphs 1 to 18, wherein at least one of said acoustic sources is a water gun.

21. A marine seismic source as defined in any preceding paragraph, wherein said acoustic ceiling has an acoustic impedance of greater than $1,500,000 \text{ kg/m}^2\text{s}$.

22. A marine seismic source as defined in any preceding paragraph, wherein said acoustic ceiling has an attenuation of more than 0.5dB/m.

23. A method of conducting a seismic survey of a geological formation below water, the method comprising:

placing at least one acoustic source in the water;

placing an acoustic ceiling above said acoustic source; and

emitting an acoustic wave from said acoustic source so that at least part of said acoustic wave reflects from said acoustic ceiling, and so that the reflection of said acoustic wave from said ceiling is reduced in amplitude compared to reflection of said acoustic wave from a boundary between said water and air.

24. A method as defined in paragraph 23, which comprises analysing acoustic waves in the frequency range 1 Hz to 10 Hz reflected from said geological formation.

25. A method as defined in paragraph 23 or 24, which comprises analysing acoustic waves in the frequency range 10 Hz to 120 Hz reflected from said geological formation.

26. A method as defined in paragraphs 24 and 25, which comprises using different acoustic sources for the analysis in the 1 Hz to 10 Hz range and the 10 Hz to 120 Hz ranges, and introducing a timing difference between said different acoustic sources.

27. A method as defined in any one of paragraphs 23 to 26, which further comprises:

placing at least one secondary acoustic source in the water; and

emitting an acoustic wave from said secondary acoustic source so as to produce a primary pulse travelling downwardly from said secondary acoustic source, and a ghost pulse which travels substantially parallel with said primary pulse after reflection from the surface of said water;

wherein no acoustic ceiling is positioned in the path of said ghost pulse.

28. A method as defined in paragraph 27, wherein a timing delay is introduced between the acoustic waves produced by said at least one acoustic source and said at least one secondary acoustic source.

29. A method as defined in any one of paragraphs 23 to 28, wherein said at least one acoustic source and said acoustic ceiling form parts of a marine seismic source which has the features of any of paragraphs 1 to 22.

CLAIMS:

1. A marine seismic source arrangement for conducting a seismic survey of a solid geological formation below water, said source comprising:
 - at least one acoustic source for emitting an acoustic wave in said water, and
 - a solid acoustic ceiling positioned in use above said acoustic source;wherein said acoustic ceiling:
 - a) has a positive effective reflection coefficient so that downgoing components of said acoustic wave vertically below the source interfere constructively with components of said acoustic wave reflected from said ceiling; and
 - b) is arranged to float on the surface of said water during use.
2. A source arrangement as claimed in claim 1, wherein said acoustic ceiling has a lower surface which is continuous, or generally continuous, across the whole or the lower surface of the acoustic ceiling.
3. A source arrangement as claimed in any preceding claim, wherein said acoustic ceiling is at least 0.5 meters thick, or at least 1 meter thick, from top to bottom.
4. A source arrangement as claimed in any preceding claim, wherein said acoustic ceiling attenuates said acoustic wave so that the magnitude of the acoustic wave at the top of the acoustic ceiling is less than 75% of the magnitude of the incoming acoustic wave at the bottom of the acoustic ceiling.
5. A source arrangement as claimed in any preceding claim, wherein said acoustic ceiling attenuates said acoustic wave so that the magnitude of the acoustic wave at the top of the acoustic ceiling is less than 50% of the magnitude of the incoming acoustic wave at the bottom of the acoustic ceiling.
6. A source arrangement as claimed in any preceding claim, wherein said acoustic ceiling has an attenuation of more than 0.5dB/m at at least one frequency in any one of the ranges 1 to 10 Hz, 1 to 20 Hz or 1 to 40 Hz, preferably at all frequencies in any one of said ranges.

7. A source arrangement as claimed in any preceding claim, wherein said acoustic ceiling has sufficient structural strength not to be perforated by operation of said acoustic source.
8. A source arrangement as claimed in any preceding claim, wherein said acoustic ceiling comprises a marine vessel or barge or other floating container.
9. A source arrangement as claimed in any preceding claim, wherein said acoustic ceiling comprises mud or drilling fluid
10. A source arrangement as claimed in any preceding claim, wherein said acoustic ceiling comprises the mineral Barite, BaSO₄.
11. A source arrangement as claimed in any preceding claim, wherein said acoustic ceiling comprises concrete.
12. A source arrangement as claimed in any preceding claim, wherein said acoustic ceiling comprises steel.
13. A source arrangement as claimed in any preceding claim, wherein said acoustic ceiling comprises water saturated porous rock, sand and/or gravel.
14. A source arrangement as claimed in any preceding claim, wherein at least one component of said acoustic ceiling is fully or partially water saturated.
15. A source arrangement as claimed in any preceding claim, wherein said acoustic ceiling comprises a structure comprising steel bar elements with damping springs connecting at least some of said steel bar elements.
16. A source arrangement as claimed in any preceding claim, wherein said acoustic ceiling comprises at least two layers of different materials.
17. A source arrangement as claimed in any preceding claim, wherein said acoustic ceiling comprises at least three layers of different materials.

18. A source arrangement as claimed in any preceding claim, wherein said effective reflection coefficient is greater than +0.1, greater than +0.5, or substantially equal to 1.

19. A source arrangement as claimed in any preceding claim, wherein said acoustic ceiling has said positive effective reflection coefficient at least one frequency in any one of the ranges 1 to 10 Hz, 1 to 20 Hz or 1 to 40 Hz, preferably at all frequencies in any one of said ranges.

20. A source arrangement as claimed in any preceding claim, wherein said acoustic source is physically connected to said acoustic ceiling.

21. A source arrangement as claimed in claim 20, wherein said acoustic source is connected to said acoustic ceiling by a flexible cable.

22. A source arrangement as claimed in claim 20, wherein said acoustic source is connected to said acoustic ceiling in a rigid manner, so that said acoustic source and acoustic ceiling are substantially fixed in position relative to each other.

23. A source arrangement as claimed in any preceding claim, wherein said acoustic ceiling has an acoustic impedance of greater than 1,500,000 kg/m²s.

24. A source arrangement as claimed in any preceding claim, wherein said acoustic ceiling has a length, that is a maximum dimension measured horizontally during use, of at least 2 meters or at least 10 meters.

25. A source arrangement as claimed in claim 24, wherein said acoustic ceiling has a width, that is a dimension perpendicular to said length, of at least 2 meters or at least 10 meters.

26. A method of conducting a seismic survey of a solid geological formation below water, said method comprising:

placing at least one acoustic source in said water;

floating on the surface of the water a solid acoustic ceiling above said acoustic source; and

emitting an acoustic wave from said acoustic source;

wherein said acoustic ceiling has a positive effective reflection coefficient so that downgoing components of said acoustic wave vertically below the source interfere constructively with components of said acoustic wave reflected from said ceiling.

27. A method as claimed in claim 26, wherein said acoustic source and acoustic ceiling together form a marine seismic source arrangement as claimed in any one of claims 1 to 23.

28. A method as claimed in claim 26 or 27, which comprises positioning said acoustic source directly below said acoustic ceiling when emitting said acoustic wave.

29. A method as claimed in any one of claims 26 to 28, wherein said geological formation includes basalt or salt layers.

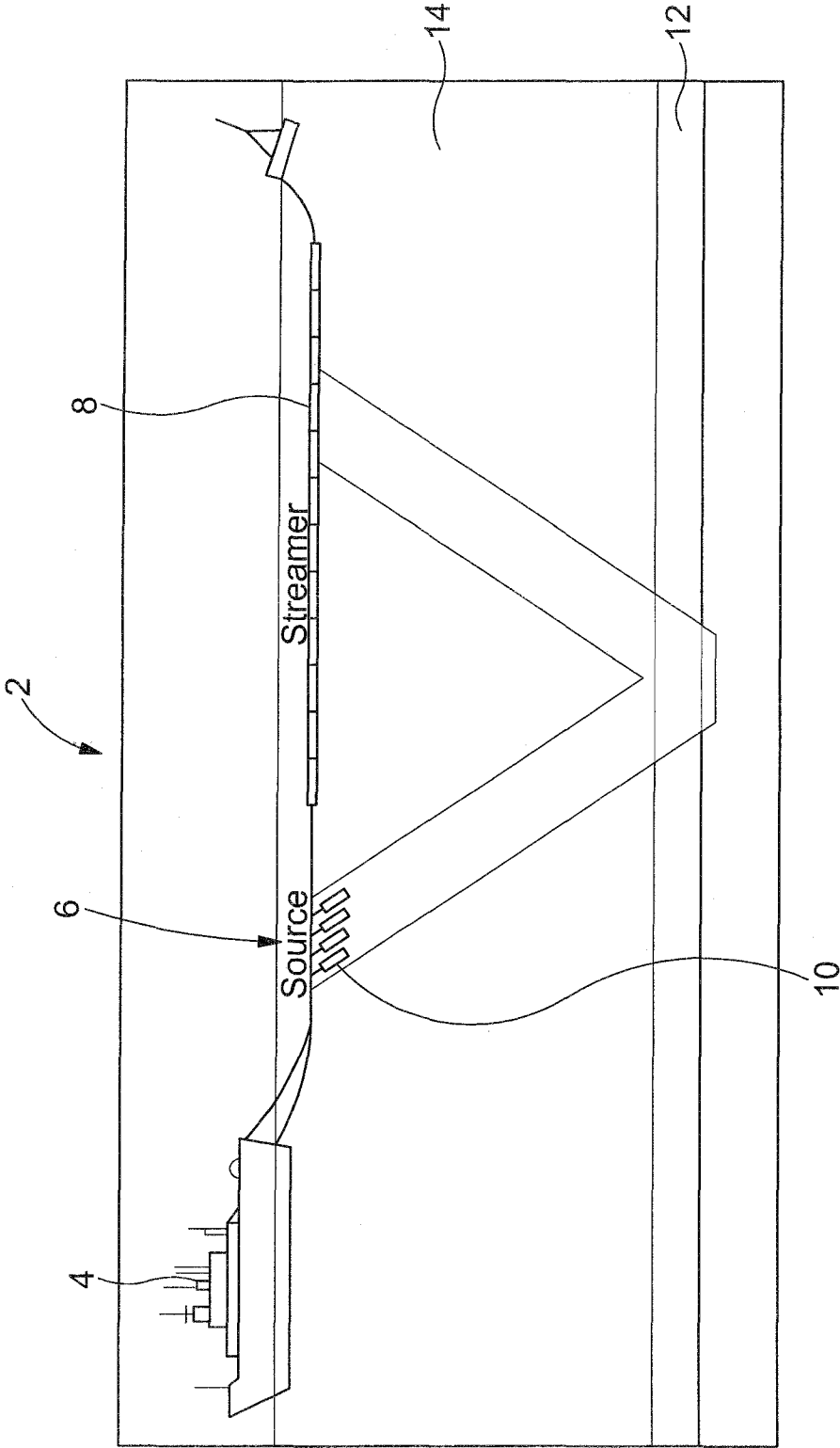
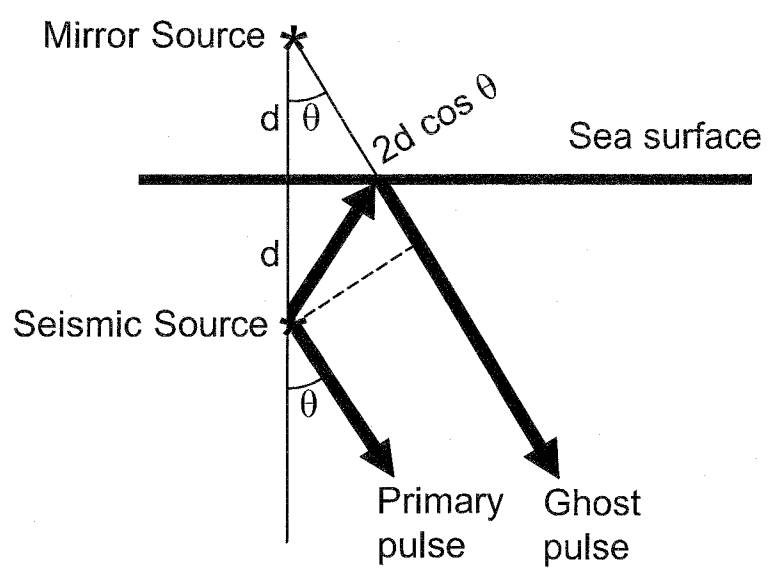


Fig 1

Fig 2

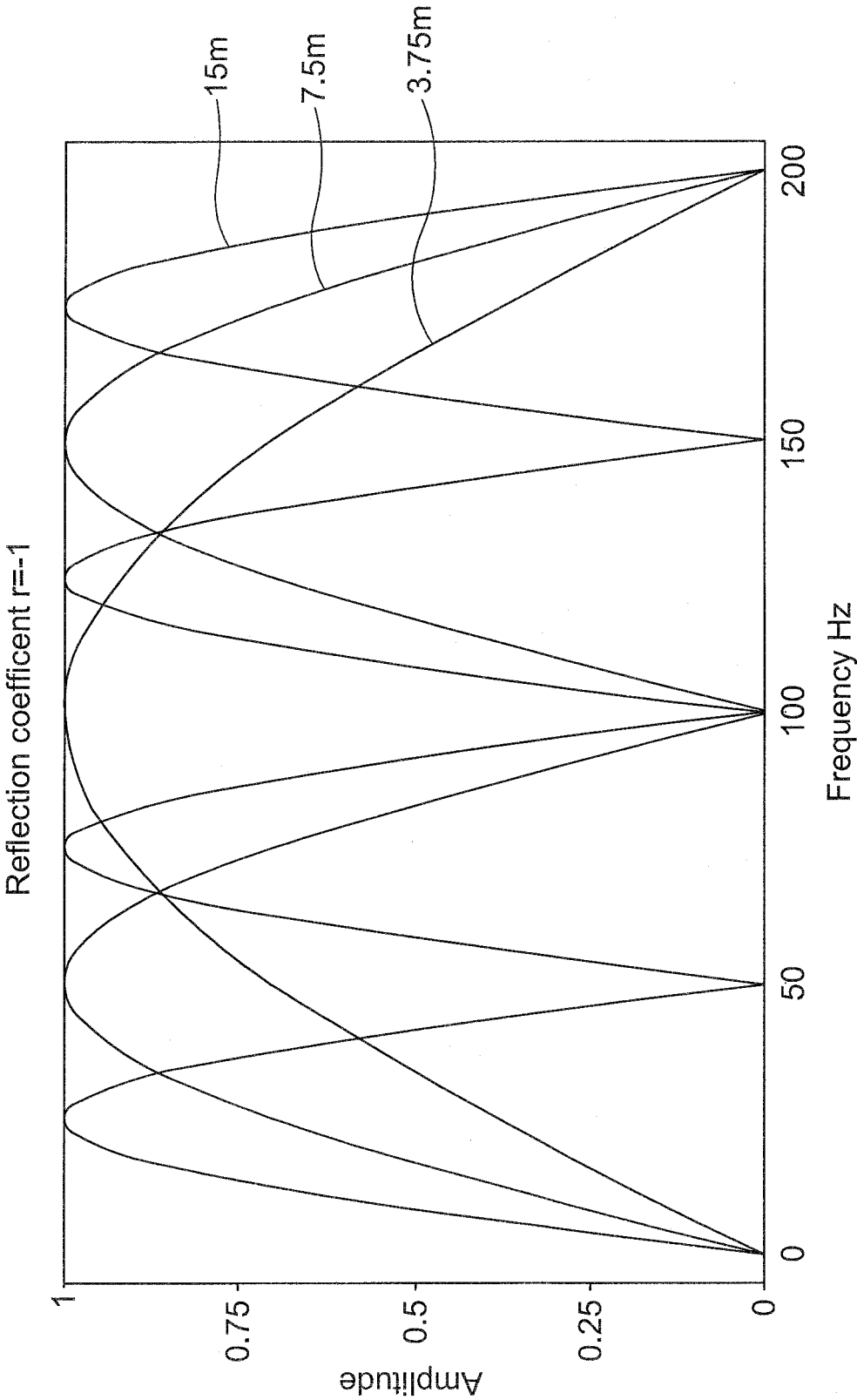


Fig 3

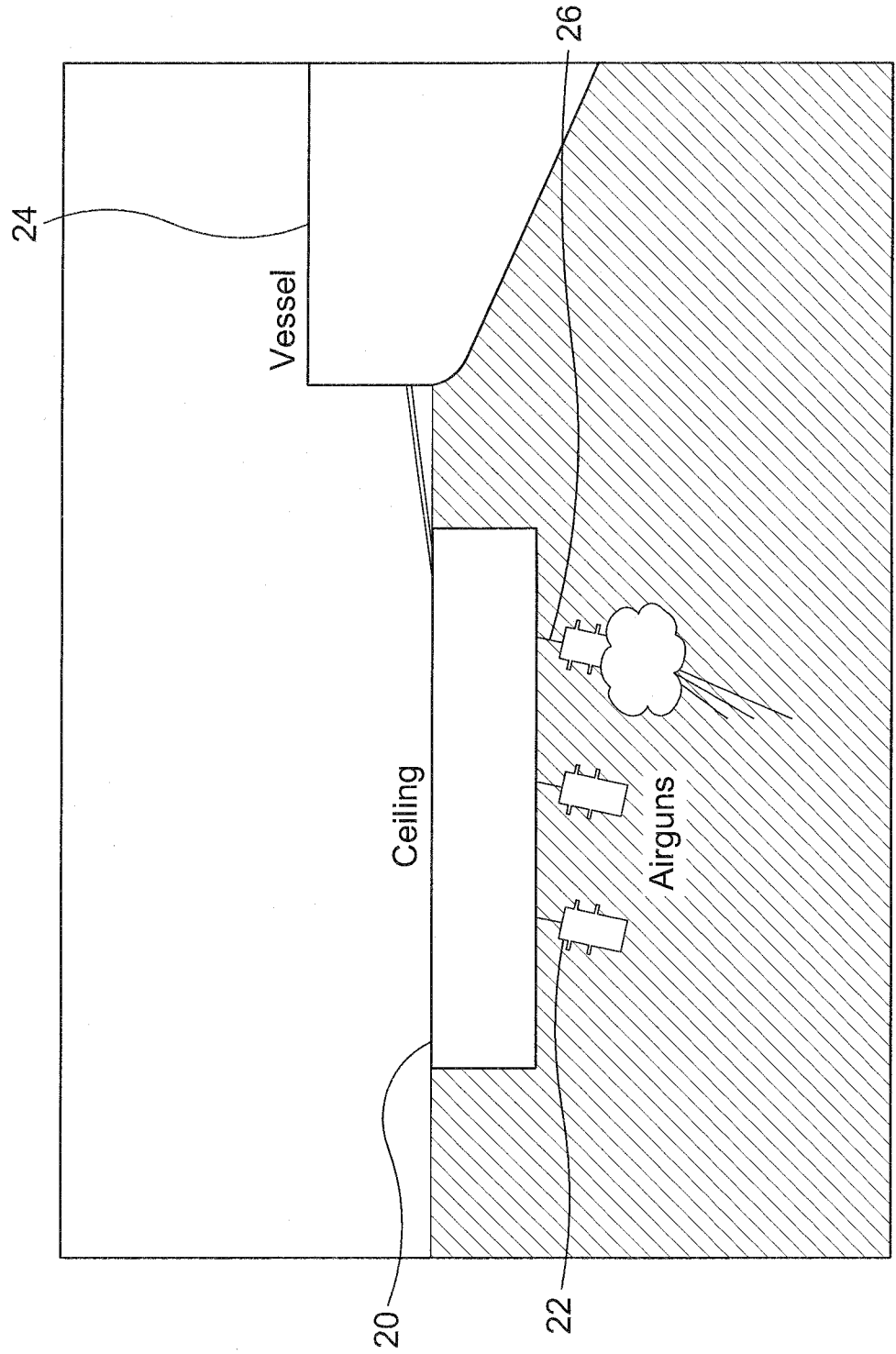


Fig 4

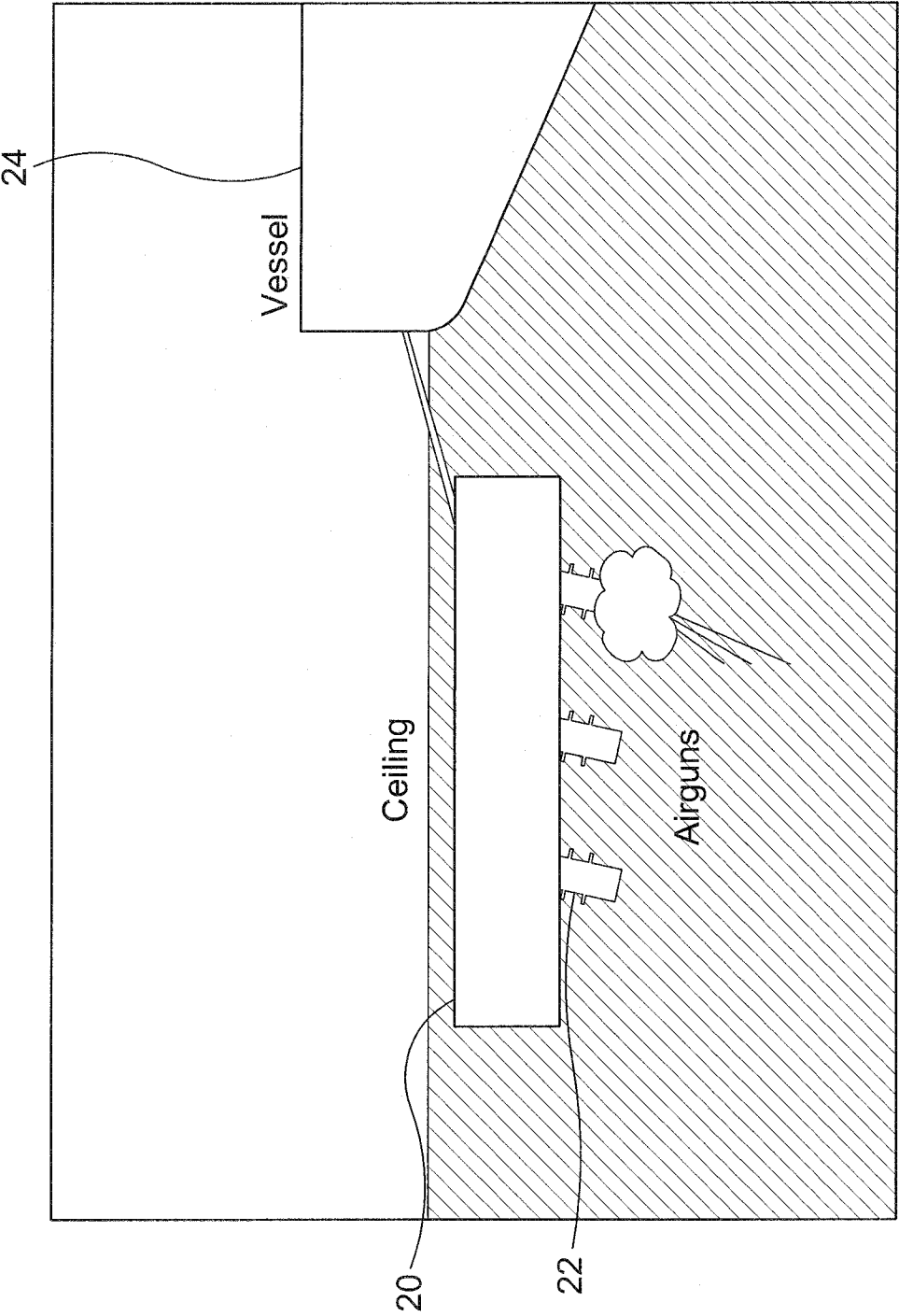


Fig 5

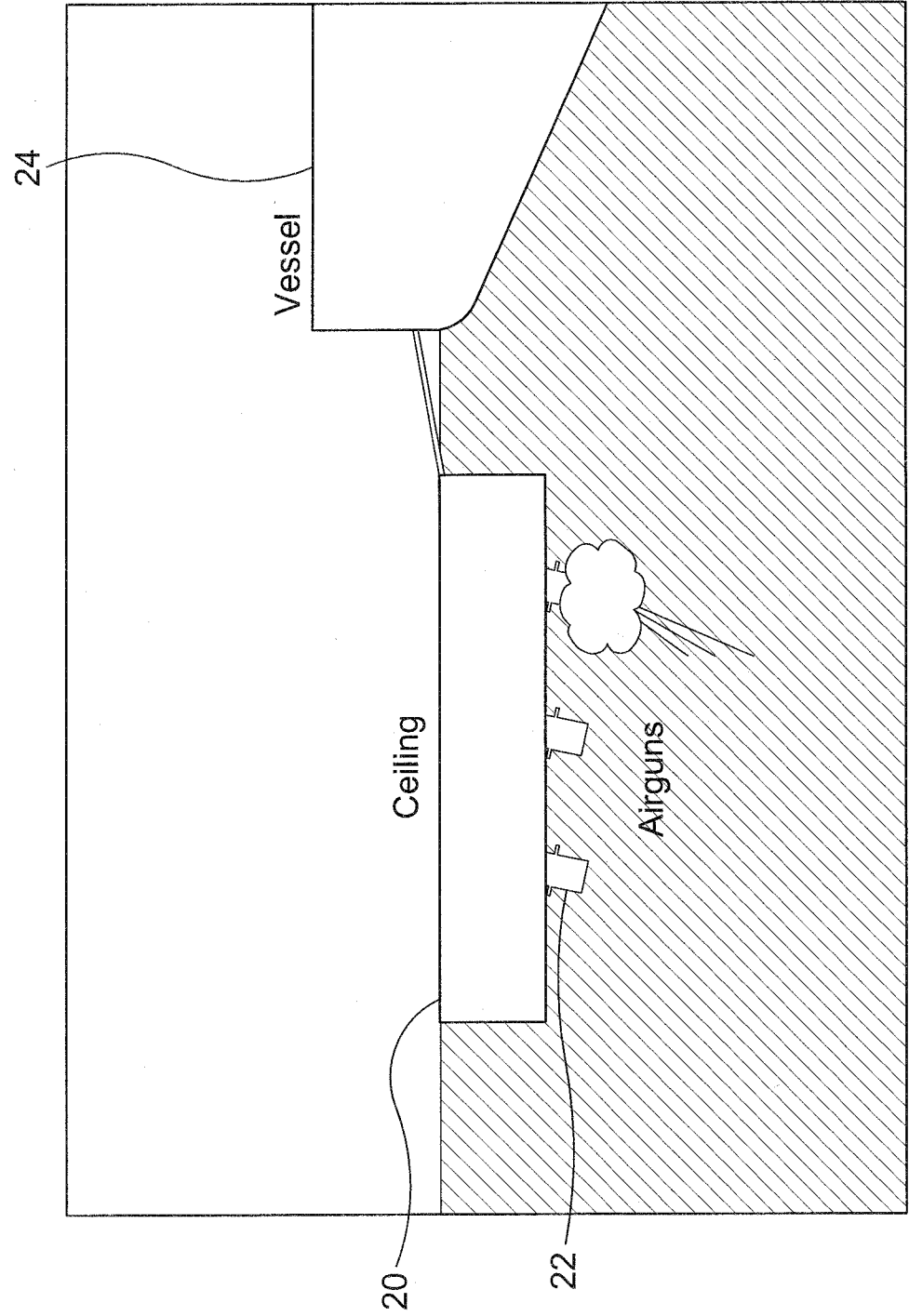


Fig 6

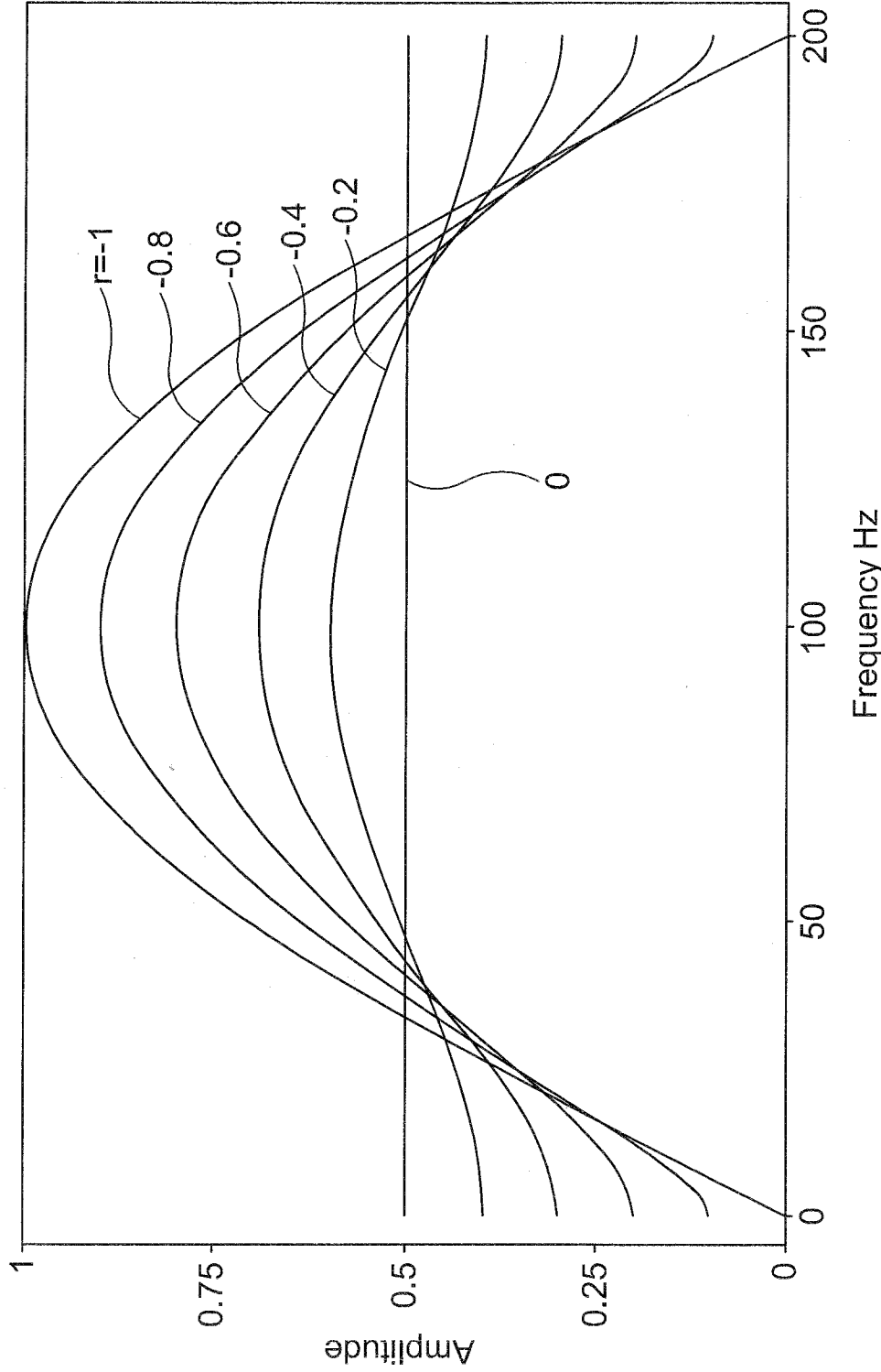


Fig 7

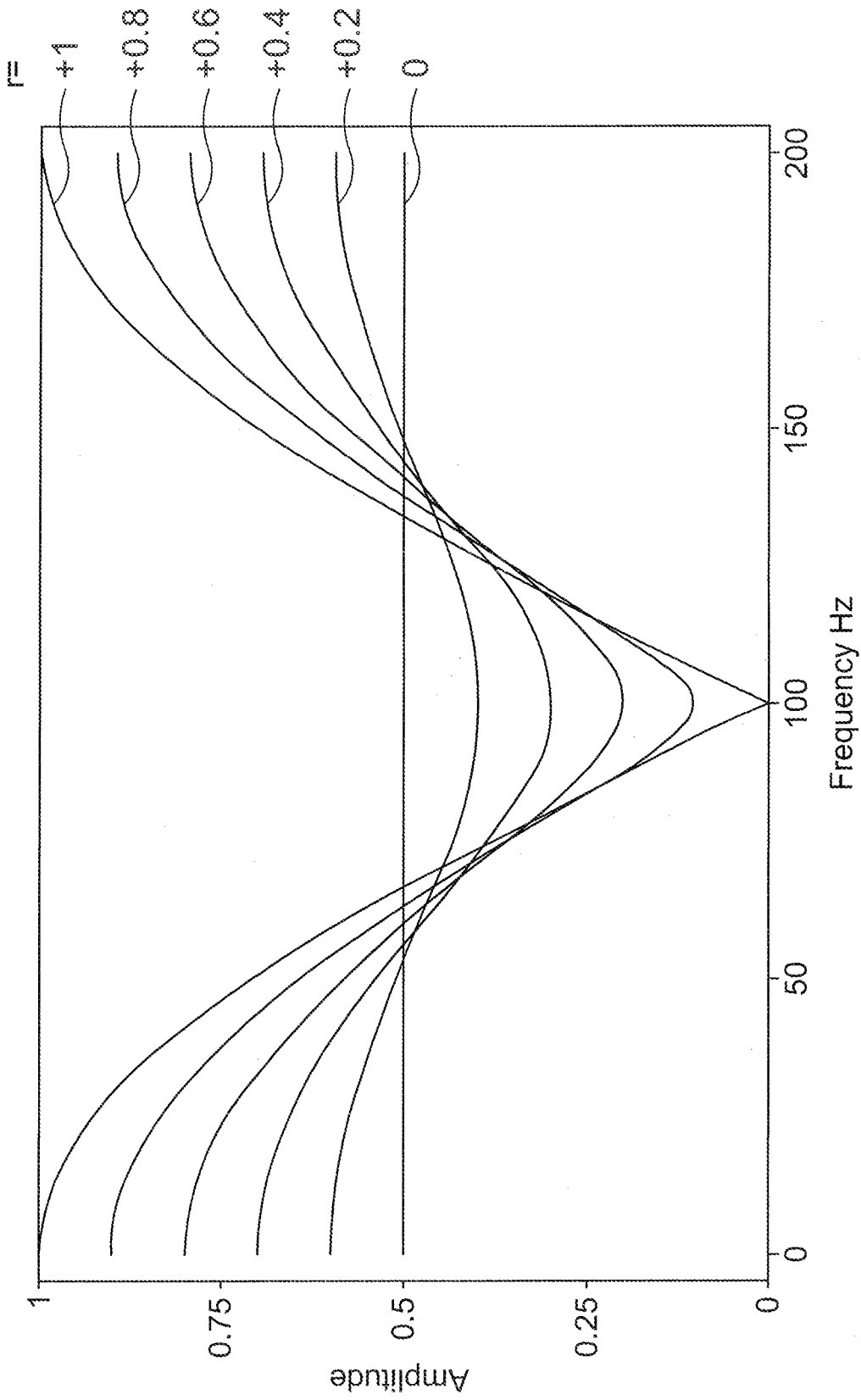


Fig 8

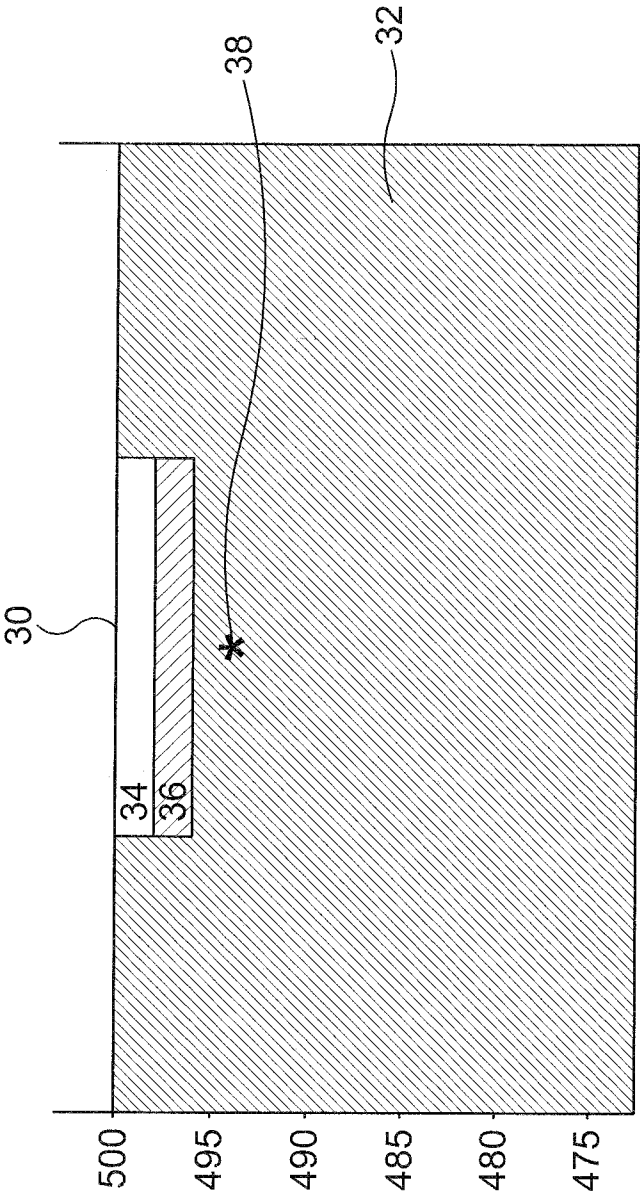


Fig 9

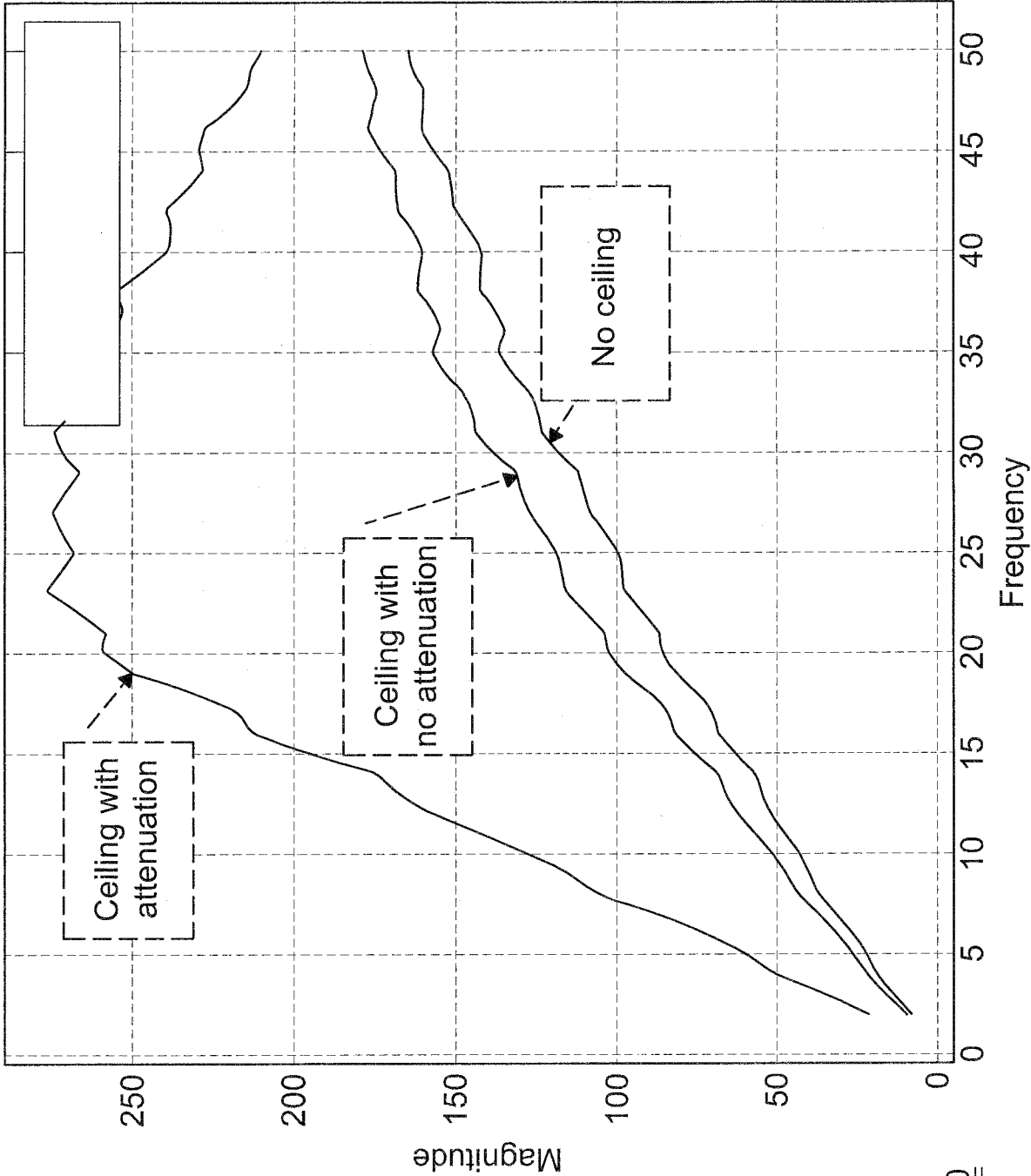


Fig 10