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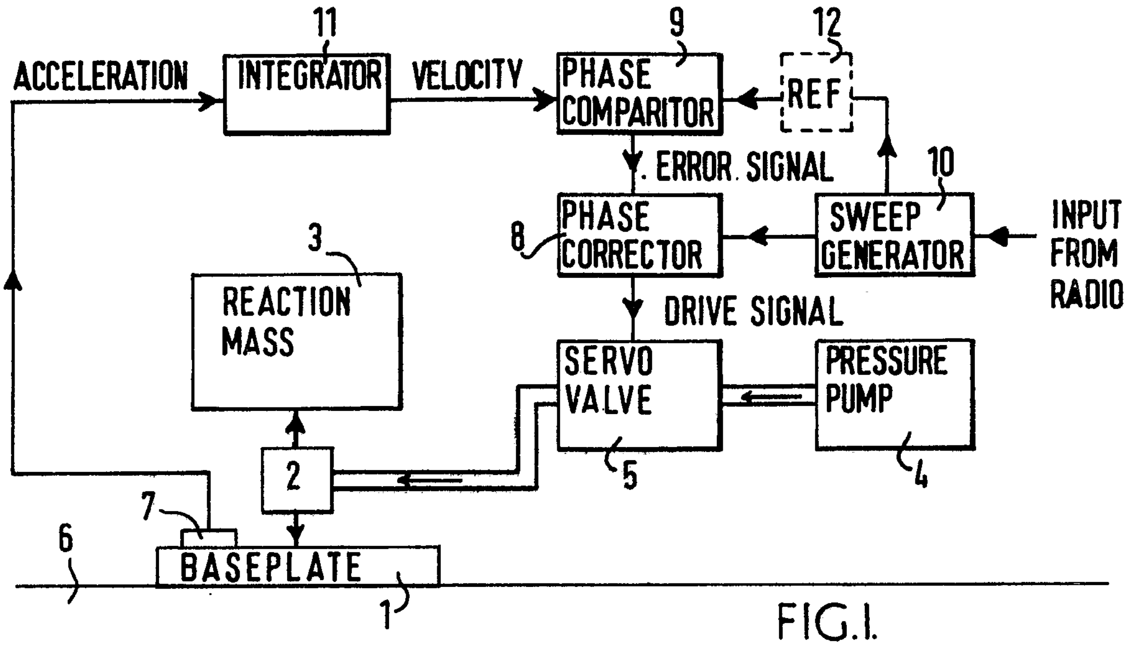
(54) Seismic Vibrator Control

(57) A method of conducting a seismic exploration wherein a moving reaction mass vibrator driven in accordance with a control signal is employed to transmit a signal into the earth, there being used to derive a sum or difference signal to maintain the movement of the reaction mass, rather than the vibrator baseplate, in a fixed phase relationship with the control signal a parameter, e.g. the reaction mass acceleration, which is in a constant phase relationship with the pressure in the transmitted wave. Where an array of vibrators is used the motions of their reaction masses, not their baseplates, are synchronized.

The drawings originally filed were informal and the print here reproduced is taken from a later filed formal copy.


ACCELERATION
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PHASE CORRECTOR
8
SWEEP GENERATOR
INPUT FROM RADIO
3
REACTION MASS
DRIVE SIGNAL
SERVO VALVE
PRESSURE PUMP
2
5
4
7
6
BASEPLATE
1

FIG.1.

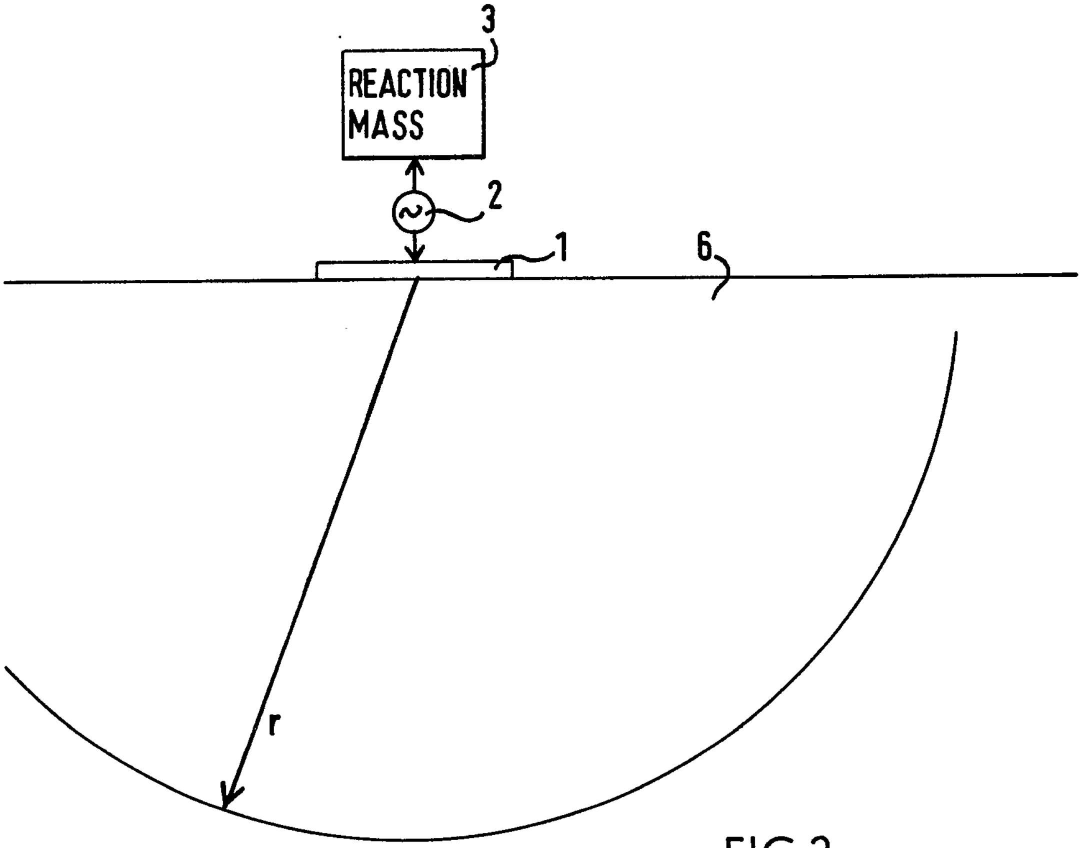
3
REACTION MASS
2
1
6
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FIG.2.

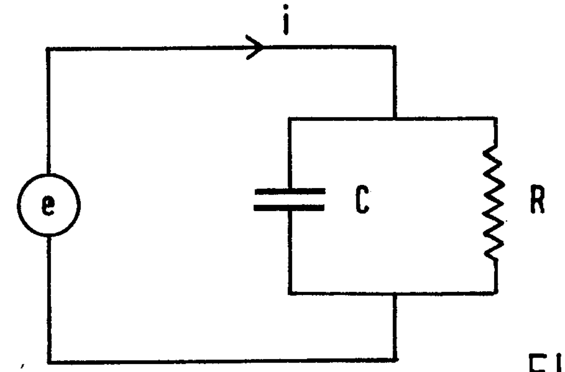


FIG.3.

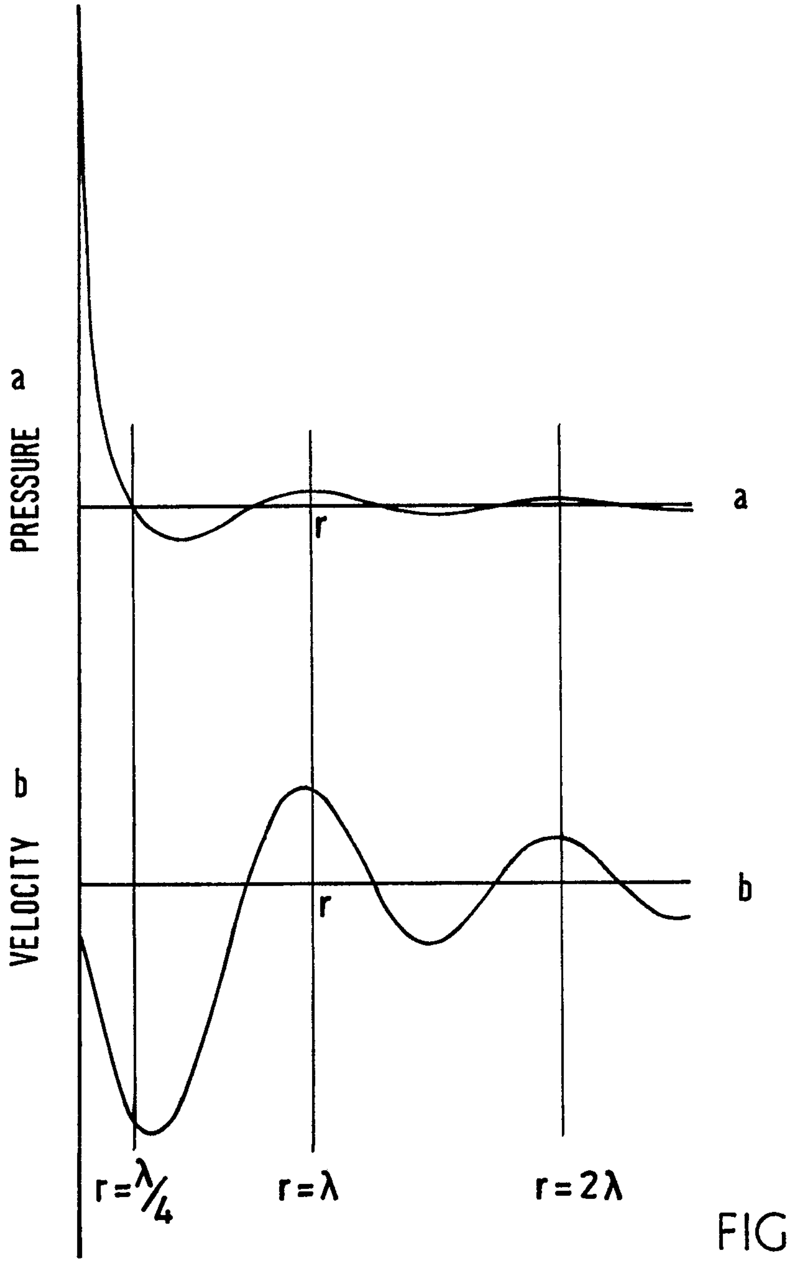
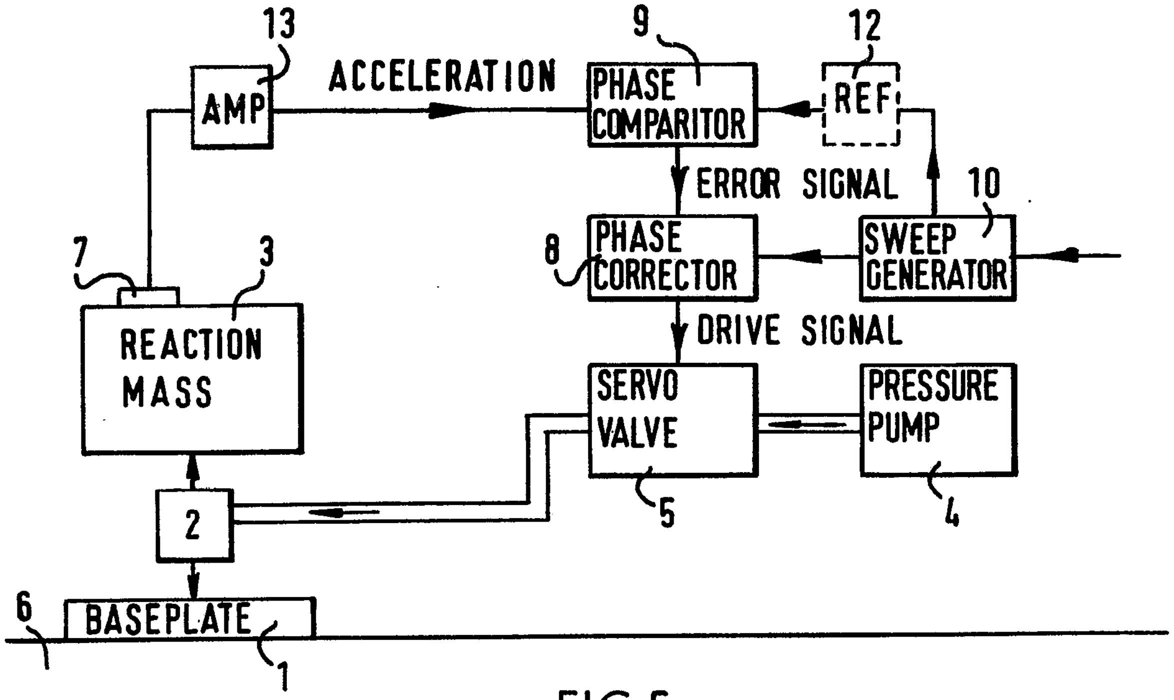


FIG.4.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DRIVE SIGNAL
SERVO VALVE
PRESSURE PUMP
2
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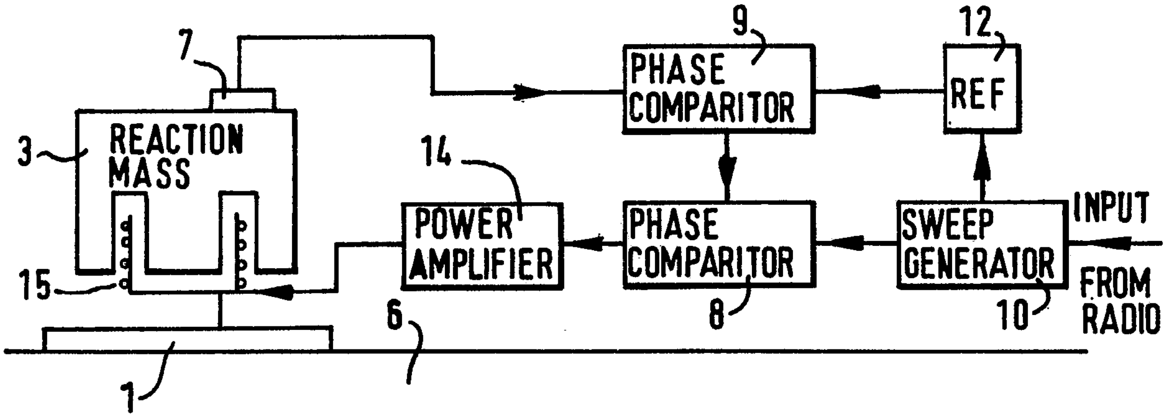
6
BASEPLATE
1

FIG.5.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9
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PHASE COMPARITOR
REF
3
REACTION MASS
14
POWER AMPLIFIER
PHASE COMPARITOR
SWEEP GENERATOR
INPUT
FROM RADIO
15
6
8
10
1

FIG.6.

SPECIFICATION

Seismic Vibrator

This invention relates to a method of conducting a seismic exploration and to apparatus for use in such a method.

There is well-known a seismic exploration technique in which a vibrator transmits into the earth a continuously varying, or "swept" frequency signal of several seconds duration. The wave is reflected from the various layers that exist in the earth, and is subsequently detected by an array of geophones which constitute the usual reflection spread. Alternatively the technique may be designed to detect refracted arrivals from the vibrator, both such techniques being well-known in the art of seismic exploration. Whatever the application, the signal received by the geophones in the array is the superposition of several swept frequencies each one representing a reflected or refracted arrival or any of the various modes of source generated interference that will occur.

At this stage in the process it is impossible to estimate the arrival time of an event simply by looking at a recording of the geophone signals; a further process is required to compress the swept frequency signals into discrete pulses. The usual method of achieving this is by means of cross-correlation.

For example, the input frequency to the vibrator might start at 100 Hz and decrease linearly with time to finish at a frequency of 10 Hz over a total period of 15 seconds. Now the autocorrelation coefficients of that sweep when plotted as a time series will produce a perfectly symmetrical pulse with a time period of only 9 milliseconds or so. This is the result that is desired when the input signal to the vibrator is cross-correlated with a swept frequency reflected from a sub-surface layer.

However, it is well-known that if the signal detected by the geophone has, during its progress from the sweep generator, suffered a phase distortion, then the pulse obtained by cross-correlation will be distorted and will consequently degrade the resolution of events on the seismic record. Nevertheless, the method is no more sensitive to phase distortion than conventional methods of exploration when it occurs in the body of the earth, in the geophones or in the recording instruments, but where phase distortion peculiar to the techniques described above is likely to occur is between the sweep generator and the point at which the vibrator delivers its signal into the earth. This description will be confined to those phase shifts associated with the vibrator and the complex input impedance of the earth.

In accordance with current practice it will be assumed that a sweep generator delivers a pre-determined sweep frequency which does not vary in band-width, phase or duration; this will be called the CONTROL SWEEP.

It should also be taken into account that, in practice, the seismic source is often an array of two, three or more vibrators spaced along the line of traverse, and that all vibrators are driven from a common control sweep.

The majority of seismic vibrators in use today contain electrically controlled hydraulic systems which are capable of delivering energy at the rate of thousands of Joules per second into the earth. These machines contain a number of hydraulic control valves, feed pipes and cylinders all of which introduce unavoidable phase delays in the sweep. It is also well-known that the compliance of the earth has an effect on the phase response of the vibrator. Therefore, in view of the phase requirement which has been outlined above, a servo control system is employed to ensure that the apparent output of the vibrator follows the phase of the control signal, or that it maintains some constant phase relationship with the control signal.

Figure 1 is a block diagram illustrating the main components of a typical known hydraulic vibrator in which a mass (3) is accelerated against a baseplate (1) which is in close contact with the ground (6). The accelerating force is supplied by an hydraulic cylinder (2) which is driven by a pressure pump (4) through a servo valve (5). In practice there is usually some additional weight (not shown) applied to the baseplate in order to maintain its contact with the ground when the acceleration of the reaction mass exceeds that of its own weight. All of these are components essential to a vibrator, the details of which are not important to this disclosure.

The remaining components are those associated with the drive control and phase compensation of a known vibrator. A sweep generator (10), or it may be an amplifier the input of which is supplied by a remote sweep generator by means of a radio link, drives the servo valve (5) via a phase corrector (8). The output from an accelerometer (7) mounted on the baseplate is integrated in an integrator (11) so that a signal proportional to the baseplate velocity is supplied to the phase comparator (9). The comparator compares the baseplate velocity signal with the output from the signal generator, or with a signal which has some predetermined phase delay applied by a reference phase unit (12), so that when they do not agree an error signal is supplied to the phase corrector (8), which controls the servo valve. Thus the method of phase compensation is based upon the assumption that:

(a) The velocity of the *baseplate* represents the particle velocity of the compressional wave which radiates from the vibrator, and

(b) In the case of a plurality of vibrators spaced along the line of traverse and driven from a common control sweep, the optimum state for the plurality of vibrators exist when their *baseplate* motions are in phase.

Therefore, in practice, an array of vibrators is controlled from a common sweep generator, and the subsequent cross-correlation is made using the transmitted sweep, or a sweep which is modified by the reference phase unit (12) which is standard for all vibrators in the array, which is phase locked to the baseplate velocity.

We have now realized that the velocity of the baseplate is a function of the complex input impedance of the earth, and therefore does not bear a constant phase relationship with the compressional wave.

According to a first aspect of the present invention there is provided a method of conducting a seismic exploration wherein a moving reaction mass vibrator driven in accordance with a control signal is employed to transmit a signal into the earth, the acceleration of the reaction mass being used to derive a sum or difference signal to maintain the movement of the reaction mass in a fixed phase relationship with the control signal.

According to a second aspect of the present invention there is provided a vibration source for use in seismic exploration, which includes a seismic vibrator having a movable reaction mass arranged to be driven in accordance with a control signal, an accelerometer for detecting the acceleration of the reaction mass and for producing a signal proportional thereto, and means for comparing the control signal with the signal obtained from the accelerometer to derive a sum or difference signal for maintaining the movement of the reaction mass in a fixed phase relationship with the control signal.

The invention also provides in a third aspect a seismic vibrator having a movable reaction mass for generating vibrations and an accelerometer arranged to detect the acceleration of the reaction mass.

Additionally, a fourth aspect of the present invention provides a method of conducting a seismic exploration in which a plurality of seismic vibrators each having a moving reaction mass is employed, in which the motions of the reaction masses of all of the vibrators are synchronized.

The essence of the present invention lies in the realization that the acceleration of the reaction mass is directly proportional to the pressure in the wave, which propagates uniformly into the far field and that the control sweep should be phase locked to the *acceleration* of the *reaction mass* rather than the velocity of the baseplate. It has thus also been realized that it is the motion of reaction masses, not the baseplates, that should be synchronized when vibrators are used in an array.

The following discussion presents the mathematical reasoning upon which the present invention is predicated; however, this discussion is for explanatory purposes only and the invention is not to be bound thereto or thereby.

When the effective diameter of a baseplate is small compared with the wavelength of the seismic wave it generates, the following conditions will prevail:

1. The load presented by the earth is that of a heavily damped compliant system with a complex input impedance.

2. The baseplate may be regarded as a point source, or more correctly, as a surface generating the spherical wave at some small distance from its effective point source.

Dealing first of all with condition 1. above; Figure 2 represents the basic seismic vibrator in which a drive unit (2) supplies an oscillatory drive force between the reaction mass (3) and the baseplate (1) which is in contact with a medium (6) representing the earth. It is assumed for the sake of simplicity that the drive force does not exceed the weight of the reaction mass, therefore any additional hold down weight is unnecessary; nevertheless, with or without a properly isolated hold down weight, the following equations apply:

Let the dynamic force acting upon the base plate be f then:

$$f = Ma \qquad (1)$$

where

M=the mass of the reaction mass
a=acceleration of the reaction mass.

The variation in pressure applied to the earth immediately underneath the baseplate will be P where:

$$P = \frac{Ma}{S} \qquad (2)$$

where S is the area of the baseplate.

Although the vibrator would normally transmit a swept frequency signal it is more convenient to examine phase in the steady state, when Ma is a constant frequency oscillatory force. Therefore, the variation in pressure may be expressed as follows:

$$\frac{Ma}{S} = P = A \cos \omega t \qquad (3)$$

where A is some peak pressure corresponding to a peak acceleration of the reaction mass.

Now if the load impedance presented to the baseplate were purely resistive then its velocity would be exactly in phase with the input force, but if, on the other hand, it was possible for the load to be purely reactive, then velocity would be exactly 90° out of phase with force. In practice, however, the earth contains both reactive and resistive components, the reactive ones being associated with its density and compliance, and the resistive ones with frictional and radiation losses. Therefore, the baseplate responds to a complex load impedance, and when its diameter is small compared with wavelength, the impedance is dominated by the component associated with elasticity. Consequently the phase difference between input force and velocity lies somewhere between 0° and 90°, depending upon the ratio of the real and imaginary components in its complex load impedance.

The electrical analogy in Figure 3, although not essential to this disclosure, illustrates, in what might be more familiar terms, the nature of the load seen by the baseplate. The combined effects of the earth's compliance and density (including the baseplate's own mass, although this should be small compared with that of the earth it sets in motion) are represented by the reactive component C; the component which accounts for the power dissipated in the earth is represented by the resistor R. Other parameters in the analogy are as follows:

P=voltage, e
u=current, i
ω=angular frequency

The electrical load impedance Z may be written:

$$Z=\frac{e}{i}=\frac{1}{\frac{1}{R}+j\omega C} \qquad (4)$$

It follows that:

$$i=\frac{e}{R}+je\omega C \qquad (5)$$

The phase angle between current and voltage (and therefore by analogy between velocity and pressure) is θ where:

$$\theta=\tan^{-1}R\omega C \qquad (6)$$

If the reactive component be represented by an inductance, equation (5) becomes:

$$i=\frac{e}{R}-j\frac{e}{\omega L}$$

and the corresponding equation (6) becomes:

$$\theta=\tan^{-1}\frac{R}{\omega L}$$

The choice of electrical component is not important in this description since the effect it is intended to illustrate is that a similar equation may be written to describe the motion of the baseplate in which:

$$u=PK+j\,PX \qquad (7)$$

where K is a real quantity and X is imaginary.

Turning now to condition 2 above; it may be assumed that the pressure immediately under the baseplate is equivalent to the pressure in a spherical wave at some small distance from its effective point source. Similarly, the baseplate velocity is equivalent to the particle velocity in the wave. Therefore the complex impedance presented to the baseplate might be (at low frequency) equivalent to the impedance presented to a spherical wave near its source; this is confirmed in the following analysis.

The equations describing pressure and particle velocity in the spherical wave, appropriate for the small motions excited by the vibrator, may be written as follows:

$$P_w=\frac{1}{r}\frac{d\phi}{dt} \qquad (8)$$

$$u_w=\frac{1}{pcr}\frac{d\phi}{dt}+\frac{1}{pr^2}\phi \qquad (9)$$

where

$$\phi=F(t-\frac{r}{c})$$

representing some function of time t and radial distance r from the source, and:

P_w=pressure in the wave
u_w=particle velocity in the wave
p=density of the medium
c=velocity of propagation.

In the steady state condition described in equation (3) above, equations (8) and (9) may be written:

$$P_w=\frac{A}{r}Cos(\omega t-\frac{2\pi r}{\lambda}) \qquad (10)$$

$$u_w=\frac{A}{pcr}Cos(\omega t-\frac{2\pi r}{\lambda})+\frac{A}{\omega pr^2}Sin(\omega t-\frac{2\pi r}{\lambda}) \qquad (11)$$

where A represents some constant peak pressure and λ is the wavelength where:

$$\lambda=\frac{2\pi c}{\omega}$$

Equation (10) indicates that the pressure wave propagates with an amplitude inversely proportional to radial distance r. This describes the amplitude decay in a spherical wave in which the total energy is conserved as the sphere expands. Note that the second term in the bracket indicates that the phase changes uniformly with distance from the source, that is to say the pressure wave propagates without phase distortion into the far field. This is illustrated in Figure 4a in which the steady state pressure amplitude is plotted against radial distance from the source when t is held constant.

Equation (11) describes the corresponding amplitude of the particle velocity; this shows the effect due to a change in the reactive part of the load presented to the wave as it propagates. Note that there are two terms in the equation, the first is a cosine function proportional to 1/r, and the second is a sine function proportional to $1/r^2$. The sine term will predominate when r is small, but as r increases, the cosine term will become more significant until, in the far field, it becomes the predominant one. Consequently the particle velocity tends to be 90° out of phase with pressure near the source, but they are virtually in phase with each other at distances greater than a wavelength or so. The effect is illustrated in Figure 4b where particle velocity u_w may be compared with pressure on the same radial distance scale.

Equations (8) and (9) may also be written in the form:

$$P_w=\frac{A}{r}e^{j\omega(t-\frac{r}{c})} \qquad (12)$$

$$u_w=\frac{A}{pcr}e^{j\omega(t-\frac{r}{c})}+\frac{A}{j\omega pr^2}e^{j\omega(t-\frac{r}{c})} \qquad (13)$$

then from (12)

$$A=\frac{P_w r}{e^{j\omega(t-\frac{r}{c}}}$$

which when substituted for A in (13) gives:

$$u_w=\frac{P_w}{pc}+\frac{P_w}{j\omega pr} \qquad (14)$$

Thus equation (14) describes an effect similar to that in equation (7); the only difference being that the radical distance r now appears in the denominator of the imaginary term. This indicates how the reactive component in the impedance Za diminishes with radial distance until at several wavelengths it can be neglected where:

$$Za=\frac{P_w}{u_w}=pc \qquad (16)$$

Now, although the impedance presented to the spherical wave can only be approximately equivalent to that presented to the baseplate, it will be clear that baseplate velocity is not a reliable monitor of the compressional wave, since the impedance at the source must determine its amplitude and phase relationship with pressure.

Thus our findings for the situation that exists when a vibrator is transmitting a swept frequency signal into the earth may be summarized as follows:

1. The baseplate velocity cannot be relied upon to be in phase with the compressional wave it generates.
2. The pressure wave propagates without phase distortion into the far field.
3. In the far field, that is, at radial distances greater than a wavelength or so at the lowest frequency present, the particle velocity in the wave is virtually in phase with pressure at all frequencies. (Subject to the usual boundary effects which would also apply to the plane wave).

From which we conclude that the control sweep should be phase locked to the acceleration of the reaction mass, since it is the only parameter likely to be in phase with the pressure in the transmitted wave.

We also conclude that, when the seismic source is an array of vibrators, their reaction masses should be synchronized in order that the individual compressional waves they generate will bear the correct phase relationship in the far field.

Figure 5 illustrates the preferred method of phase compensating in accordance with the foregoing description.

The hydraulic system, and its control circuits, are identical with that shown in Figure 1; in which the sweep generator, or radio link, supplies the signal which drives the servo valve (5) via the phase corrector (8). The difference resides in the fact that the accelerometer (7) is now attached to the reaction mass so that a signal proportional to its *acceleration* is supplied to the phase comparator (9). (Note that the amplifier (13) is not an integrator as in Figure 1). It may also be necessary to invert the accelerometer signal in order to supply the feedback with the correct polarity, but that is trivial. Thus, the motion of the reaction mass is locked to the drive signal, and in turn, to all other vibrators in the array.

Figure 6 illustrates how the method may be applied to an electromagnetic vibrator. Here a similar phase corrector (8) supplies a power amplifier (14) which drives the electrodynamic (moving coil) unit (15). Thus the motion of the reaction mass is locked to the reference signal as before.

The method would apply to any similar seismic wave generator in which a force is acting upon a baseplate. The kernel of the invention being that the applied force, or its acceleration, is the only parameter likely to bear a constant phase relationship with the compressional wave it generates.

It is to be understood therefore that the invention in its broadest sense is restricted only to the concept of employing, to derive a phase lock for controlling at least one seismic vibrator, a parameter which is in a constant phase relationship with the pressure in the transmitted wave.

Claims

1. A method of conducting a seismic exploration wherein a moving reaction mass vibrator driven in accordance with a control signal is employed to transmit a signal into the earth, there being used to derive a sum or difference signal to maintain the movement of the reaction mass in a fixed phase relationship with the control signal a parameter which is in a constant phase relationship with the pressure in the transmitted wave.

2. A method according to claim 1, wherein said parameter is the acceleration of the reaction mass.

3. A method according to claim 2, wherein a signal proportional to the acceleration is integrated to provide a signal proportional to the velocity of the reaction mass.

4. A method according to claim 2, wherein a signal proportional to the acceleration is integrated twice to provide a signal proportional to the displacement of the reaction mass.

5. A method according to claim 1, wherein said parameter is the velocity of the reaction mass.

6. A method according to claim 5, wherein a signal proportional to the velocity is integrated to provide a signal proportional to the displacement of the reaction mass.

7. A method according to claim 5, wherein a signal proportional to the velocity is differentiated to provide a signal proportional to the acceleration of the reaction mass.

8. A method according to claim 1, where said parameter is the displacement of the reaction mass.

9. A method according to claim 8, wherein a signal proportional to the displacement is differentiated to provide a signal proportional to the velocity of the reaction mass.

10. A method according to claim 8, wherein a signal proportional to the displacement is differentiated twice to provide a signal proportional to the acceleration of the reaction mass.

11. A method according to any preceding claim, wherein any phase shift introduced by integration or differentiation is removed or compensated for.

12. A vibration source for use in seismic exploration which includes at least one seismic vibrator having a movable reaction mass arranged to be driven in accordance with a control signal, means for detecting the acceleration velocity or displacement of the reaction mass and for producing a signal proportional thereto, and means for comparing the control signal with the signal obtained from said detecting means to derive a sum or difference signal for maintaining the movement of the reaction mass in a fixed phase relationship with the control signal.

13. A vibration source according to claim 12, wherein said detecting means comprises an accelerometer.

14. A vibration source according to claim 13, wherein said detecting means comprises a velocity meter.

15. A vibration source according to claim 13, wherein said detecting means comprises a displacement meter.

16. A vibration source according to any of claims 12 to 15, wherein said comparing means includes a differentiator cator or integrator for differentiating or integrating the signal obtained from the detecting means.

17. A vibration source according to claim 16, wherein said comparing means is arranged to compensate for or remove any phase shifts caused by differentiation or integration of said signal.

18. A vibration source as claimed in claim 12 and substantially as hereinbefore described.

19. A seismic vibrator having a movable reaction mass for generating vibrations and means arranged to detect the acceleration, velocity or displacement of the reaction mass.

20. A method of conducting a seismic exploration in which a plurality of seismic vibrators each having a moving reaction mass is employed, in which the motion of the reaction masses of all of the vibrators are synchronized.

21. A method according to claim 20, wherein each seismic vibrator is as claimed in claim 19.

22. The features hereinbefore disclosed, or their equivalents, in any novel selection.

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