A geophone system with a mechanical transducer and an electronic processing device, the mechanical transducer comprising an inertial mass and a force transducer, the inertial mass being adapted to be excited by an input acceleration signal and by the force transducer, the excitation being detected by a sensor element, said force transducer being controlled by the electronic processing device, which electronic processing device comprises an analog/digital converter being controlled by the sensor element; the sensor element (4) detects the velocity of the inertial mass (2) and controls the analog/digital converter (8) by means of an amplifier (5) with a very high gain factor, the output of the analog/digital converter (8) being connected with the input of a digital/analog converter (11), and the output of this digital/analog converter (11) controlling the force transducer (12).
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A geophone system.

The invention relates to a sensor for measuring mechanical vibrations, in particular seismic waves, comprising a mechanical transducer with an electronic processing circuit. The sensor transduces the acceleration into a digital output signal.

For measuring a seismic signal, use is made of seismometers or geophones. These geophones are, generally, passive analog sensors connected in series in groups and are connected with a measuring station. By a movement of the geophone, a voltage is induced in a coil which is movably suspended in the magnetic field of a permanent magnet. To achieve a high sensitivity, the mass of the magnet is large, which unfavourably influences the coupling at high frequencies between the geophone and the ground in which it is implanted.

The analog connection between the geophones and the measuring station is sensible for disturbances by external electro-magnetic fields.

In the measuring station, the analog output signal of the geophones is amplified, sampled and digitized. Because of the high demands put on the resolution, the analog/digital converter and the anti-alias filter required to that end are so sensitive to component tolerances that manufacturing in IC-technology is almost impossible.

Not properly operating geophones can cause much damage to the collected seismic data, which damage will become only apparent during data processing, and recovery thereof is, then, not possible anymore. In order to prevent this, geophones are tested in the field.

From US-A 3 429 189 (H.F. Krabbe) an accelerometer is known producing a digital output signal. The sensor assembly consists of a sensor element determining the position of an inertial mass and a drive coil exerting a repositioning force on the inertial mass. When the output value of the position sensing element exceeds a positive or negative value, a current pulse is sent through the drive coil. A Lorentz force
is exerted thereby on the inertial mass, which is opposite to the force caused by the acceleration to be measured. The movement of the inertial mass will be reduced to substantial zero by the repositioning force. Since the duration of the current pulse is short and constant, the sum of the current pulses is proportional to the average Lorentz force and, thus, to the acceleration. By means of a digital counter the acceleration can be computed. The velocity of the mechanical input signal to be measured is proportional to the frequency of the output signal. In fact a sensor having a frequency output is obtained in this manner.

This accelerometer has some disadvantages, and is, therefore, not suitable for seismic measurements. To achieve a large dynamic range, as required in seismic measurements, the closed-loop gain should be chosen very large, so that the damping of the sensor assembly will be strongly reduced, and instability can occur. This can be prevented by including a differentiating network in the feedback loop. The combination of a position sensing element and a differentiator forms, then, a velocity sensing element. For seismic measurements it is desirable that the geophone can be used in a horizontal and a vertical orientation. In order to allow this known accelerometer to operate with the position sensing element in both orientations, the measurement range should be large enough for compensating the gravitational acceleration of the inertial mass. The measurement range should, then, be unnecessarily large, since, for using seismic measurements, a measurement range of 1 m/s^2 is sufficient.

This known accelerometer can, furthermore, only be tested by means of a mechanical input signal, which, in view of the large number of implanted geophones, will be objectionable.

It is an object of the invention to provide a digital geophone not having these disadvantages. This geophone is described in claim 1 in more detail, and has the following properties: because of the digital communication, the influence of disturbances on the cable will be small, and a large distance between the geophone and the measuring station is possible; the analog/digital converter and the anti-alias filter are so insensitive for component tolerances that
realization thereof with IC-technology is possible, so that the analog/digital converter and the anti-alias filter can be included in the geophone; the band-width of the geophone is large, and is determined by a digital filter, which leads to a large degree of freedom; the inertial mass is small, so that the geophone has a small mass as well as a small volume, ensuring a good ground coupling; on the basis of the small deviation of the inertial mass, use can be made of springs with a large transversal stiffness; the geophone is usable in any position, and is only sensible for an axial vibration; by means of a digital test signal, the transfer and distortion of the geophone can be measured.

The invention will be described below in more detail with reference to the drawing; showing in:

Fig. 1 a circuit diagram of the digital geophone according to the invention;

Fig. 2 a circuit diagram of the digital geophone, in which, by means of a second feed-back loop, an improved noise suppression is obtained;

Fig. 3 a circuit diagram of the digital geophone in which a higher sampling rate is possible;

Fig. 4 the frequency characteristic of the input signal and the test signal; also the influence of the quantization noise is visible;

Fig. 5 the mechanical transducer used in the geophone;

Fig. 6 a mechanical transducer which may be used for the geophone, in which the centering forces on the inertial mass are absorbed by a rigid construction; and

Fig. 7 a circuit element of the circuit, by means of which the geophone can be tested; this circuit measures, to that end, the harmonic distortion.

Fig. 1 shows a circuit diagram of the digital geophone according to the invention. The mechanical signals are shown by dotted lines, and the electrical signals by drawn lines.

The geophone undergoes an input acceleration $X(s)$, causing a force $F_a$ to act on the inertial mass $m$. If the resulting force of this force $F_a$ and the Lorentz force $F_l$ to be elucidated below is not equal to zero, this will have as a consequence a movement of the inertial mass $m$ of the mass-spring system.
which is detected by the velocity sensor 4. The operation of
the velocity sensor 4 will be elucidated in more detail by
Figs. 5 and 6. From a physical point of view, the sensor
element 4 has an output voltage, but in view of the
realization thereof with IC-technology, this voltage is con-
verted into an output current by the analog input amplifying
stage. The amplifying stage of the sensor element 4 is
amplified by the amplifier 5. The signal is sampled by the
sampling element 6 after the command "HOLD" of a clock 7. The
clock 7 is controlled by an external synchronisation signal
"SYNC". The sampled signal is converted by the analog/digital
converter 8 into a digital signal after the command "START" of
the clock 7. The sampling frequency f_s is high, and, at any
rate, much higher than the resonance frequency of the mass-
spring system 3. Because of the limited resolution of the
analog/digital converter 8, the latter can be realized in an
IC-process. The digital output signal Y(z) is inverted by an
inverter 9, so that the signal in the feed-back circuit is in
phase opposition to the input signal. A digital adder 10 adds a
test signal T(z) to the inverted output signal. During
measurement the signal T(z) is equal to zero. Testing the
sensor assembly 1 will be elucidated in more detail by
reference to Fig. 7. The sum signal of the adder 10 is
converted by the digital/analog converter 11 into a current
i_2. A force transducer 12 exerts a Lorentz force F_1 on the
inertial mass 2 which is proportional to the current i_2.
Because of the Lorentz force, the movement of the inertial
mass 2 will be substantially reduced to zero.

For using the geophones for seismic measurements, it is
necessary that the geophone can be tested. The transfer
function of the digital geophone can be tested by means of the
test signal T(z). By means of the digital adder 10, the test
signal is added with the inverted output signal, and, by the
digital/analog converter 11, a current i_2 is sent through the
force transducer 12. The inertial mass 2 is excited in the
same manner as by the input acceleration signal. The transfer
function Y(z)/T(z) is, in the seismic band width, almost equal
to the transfer function Y(s)/X(s), apart from a frequency in-
dependent factor. For using the test device, it is necessary
that the output signal and the test signal are being synchronized. Therefore, the "START" command will be generated by the clock by means of the external synchronization signal.

In order to reduce the number of wires, use can be made of serial communication between the geophones and the measuring station. There is, then, a common data line connecting the output signals of a group of geophones with the measuring station, and a control signal controlling the serial communication. The control signal makes use of a coding device and a specific code with which each geophone is provided. The test signal and the synchronization signal can be accommodated in the control signal by means of specific bit combinations. Such a communication system is known, and will, therefore, not be elucidated in more detail.

Fig. 2 shows an alternative circuit diagram of the digital geophone. The output current of the velocity sensing element 4 is, now, added with a current i1 to be discussed below, and is amplified by the amplifier 5'. The amplifier 5' has a very high gain factor and a low-pass transfer characteristic. The cut-off point of the frequency characteristic is very low, so that the input signal is integrated. The output signal of the low-pass filter 5' is sampled by the sampling element 6 after the command "HOLD". The analog/digital converter 8 converts the voltage into a digital output signal Y(z), and after inversion by the inverter 9 the output signal Y(z) is added to the test signal T(z). The obtained sum signal is converted, by the digital/analog converter 11, into two output currents i1 and i2. The current i1 is added to the output current of the velocity sensing element 4, and is integrated by the low-pass filter 5'. The force transducer 12 exerts a Lorentz force F1 on the inertial mass 2 which is proportional to the current i2.

The gain factors of the low-pass filter 5' should be high. The feedback in the sensor assembly 1 for a signal with a frequency zero is interrupted, since the velocity sensor 4 can only detect a movement of the inertial mass 2. The offset voltage of the low-pass filter 5' appears with a very high gain factor at the output, and, thus, limits the dynamic range of the sensor. In IC-technology, an offset compensation can be
difficultly realized, and is, therefore, expensive. By providing a second feed-back circuit with the current \( i_1 \), this disadvantage is restricted. The offset of the low-pass filter \( 5' \) is reset back by \( i_1 \), and the gain factor of the low-pass filter \( 5 \) can, now, be chosen very high without the offset restricting the dynamic range. By means of the second feed-back circuit, moreover a better suppression of the quantization noise will be obtained. This will be elucidated in more detail below.

The digital/analog converter \( 11 \) with two output currents can be realized in IC-technology by means of a current mirror with a multiple output.

Fig. 3 shows an alternative circuit diagram. In this diagram, the currents \( i_1 \) and \( i_2 \) are generated by means of two separate digital/analog converters \( 11 \) and \( 11' \). By means of the device according to this circuit diagram, the sampling rate, by means of which the digital word is converted into a current \( i_1 \), can be chosen much higher than the sampling frequency generating the current \( i_2 \). The advantage thereof is that the sampling rate is not limited by the maximum frequency of the current \( i_2 \), the voltage across the drive coil \( 12 \) then being lower than the supply voltage. By choosing a very high sampling rate for the analog/digital converter \( 8 \) and the digital/analog converter \( 11' \), components having a lower resolution can be used therefor. An arithmetical unit \( 10' \) adds, now, the inverted output signal \( Y(z) \) to the test signal \( T(z) \), integrates the sum signal, and sends, after a clock pulse of the circuit \( 7 \), the signal towards the digital/analog converter \( 11 \). The integration of the sum signal obtained by the low-pass characteristic of the arithmetical circuit \( 10' \) improves the resolution of the signal fed back.

Fig. 4 shows the frequency characteristic of the sensor assembly. The mass-spring system \( 3 \) has a resonance frequency lying within the seismic band-width, but because of the high open-loop gain, the transfer of the sensor assembly \( 1 \) within the seismic band-width will be hardly influenced by the frequency characteristic of the mass-spring system \( 3 \). For frequencies higher than the seismic band-width, the open-loop gain is small because of the low transfer function of the
mass-spring system 3 and the low-pass filter 5'. The transfer function \( Y(s)/X(s) \) of the sensor assembly 1 will then decrease with an increase of the frequency. Since the velocity sensing element 4 will only detect the movement of the inertial mass 2, the transfer function of the sensor assembly 1 will be low at frequencies lower than the seismic band-width.

The resolution of the analog/digital converter 8 is low, and quantization noise is added to the output signal. This quantization noise is uniformly distributed over the frequency band, but, because of the high open-loop gain at low frequencies, the contribution of the quantization noise to the output signal will be small. At higher frequencies the open-loop gain will decrease, and the quantization noise is no longer suppressed. In Fig. 4 the contribution of the quantization noise in the output signal is represented by a hedged area. From this Figure it appears that the contribution of the quantization noise in the seismic band-width (up to the frequency \( f_c \)) will be strongly suppressed. By selecting a very high sampling rate or by using a multiple feed-back loop, a maximum suppression of the quantization noise is obtained.

By means of a digital low-pass filter, frequencies above the frequency \( f_c \) can be suppressed. As a consequence of using the digital filter, the signal/noise ratio increases, and the resolution of the digital output signal is improved. It is possible to combine the digital filter of several geophones belonging to a group by adding the geophone data. By re-sampling the digital signal after the low-pass filter, the capacity of the data communication channel and the data storage will be used more efficiently. If the filter is made by VLSI, the filter can be accommodated inside the geophone. This technology is known per se, and will, therefore, not be elucidated in more detail.

Fig. 5 shows the mechanical transducer 13. This transducer 13 consists of an inertial mass 2 comprising a magnet 14, a distance piece 15 and inner pole pieces 16, as well as a housing 17 with a sensing coil 18, a driving coil 19, a compensation coil 20 and a tubular pole shoe 21. The inertial mass 2 is suspended in the housing 17 by means of springs 22. A movement of the inertial mass 2 changes the magnetic flux
within the sensing coil 18, and, then, induces a voltage. The sensing coil 18 is in series with the compensation coil 20, and is connected with the input of the electronic processing device. Since the magnetic field generated by the magnet 14 is null in the airgap of the compensation coil 21, a movement of the inertial mass 2 will not induce a voltage in the compensation coil 21. The drive coil 19 is connected to the electronic processing device, and is situated in the magnetic field of the magnet 14. If a current is sent through the drive coil 19, the Lorentz force \( F_l = B \cdot i \cdot l \) will exert a force on the inertial mass 2. Since the magnetic flux density \( B \) and the coil length \( l \) are constant, the Lorentz force \( F_l \) is proportional to the current \( i \). The current through the drive coil 19 has, moreover, as a consequence that by mutual induction between the drive coil 19 and the sensing coil 18 an induction voltage is induced. In order to prevent that the electronic processing device would recognize this induction voltage as a movement of the inertial mass 2, the compensation coil 20 is provided. Since the relative permeability value of the distance piece 15 is equal to that of the magnet 14, i.e. that of air, the induced voltage in the compensation coil 20 will be equal to the induction voltage in the sensing coil 18. The winding sense of both coils is, however, opposite, so that by a series connection of both coils the induction voltage as a consequence of a current through the drive coil 19 will be null.

Between these coils a capacitive coupling might arise. In order to prevent this the inner pole shoes 16 are connected, by means of a core 23, with one another and with the electric mass of the electronic processing device. The material of the core 23 is electrically conductive but magnetically non-conductive, and is, for instance, made of copper. The core 23 also serves for mechanically mounting the pole shoes 16, the magnet 14 and the distance piece 15 to the springs 22. A mechanical connection by means of glueing is possible, but, in view of the shock resistance, not attractive.

The mechanical construction according to Fig. 5 is simple, but has the disadvantage that the outer pole shoe 21 made of a material conducting the magnetic field is attracted
by the inner pole shoes 16 and the magnet 14. The springs 
should, therefore, be sufficiently rigid in the radial  
direction for creating a centering force which is sufficient 
for compensating the attraction force of the magnet 14. In 
5 Fig. 6 a mechanical transducer 13' is shown which does not 
have this disadvantage. The inertial mass 2' is, now, formed 
by the magnet 14, a distance piece 15, inner pole shoes 16 and 
an outer pole shoe 21'. The housing 17 comprises the sensing 
coil 18, the drive coil 19 and the compensation coil 20. The 
10 outer pole shoe 21' is rigidly fixed to the outer side of the 
inner pole shoes 16 by means of spokes 23'. The magnetic 
attraction force between the inner pole shoes 16, the magnet 
14 and the outer pole shoe 21' is now absorbed by the rigid 
mechanical connection. The inertial mass 2' is suspended in 
15 the housing 17 by means of the springs 22.

Fig. 7 elucidates a method for measuring the distortion 
level of the sensor 1. A read-only memory 24 contains a 
digitized sign signal. A switch 25 reads the read-only memory, 
and produces the test signal T(z). The period of the test 
20 signal T(z) is determined by the clock frequency generated by 
the clock generator 16 and a counter 27. The frequency of the 
test signal can be varied by adjusting n1. The test signal T(z) 
excites the inertial mass 2, and simulates an acceleration 
input signal X(s). The output signal Y(z) contains the 
25 response of the test signal T(z) and the acceleration signal 
X(s).

At the same time a second switch 28 reads the read-only 
memory 26 with a period determined by the clock generator 26 
and a counter 29. This test signal is generated with a fre-
30 quency which is n2/n1 times higher than the frequency of the 
first test signal. This signal is multiplied with the output 
signal of the sensor 1 by a multiplier 30. The product formed 
by the multiplier 30 comprises sum and difference frequencies 
of the output signal Y(z) and the test signal having a fre-
35 quency with an n2/n1 times higher frequency. The harmonic 
distortion in the output signal having a frequency which is 
n2/n2 times higher can be determined by measuring the 
difference in respect of a zero frequency at the output of the 
multiplier 30. The output signal V(z) is the harmonic
distortion having a frequency which is n2/n1 times the frequency of the test signal T(z). A low-pass filter 31 filters this frequency from the signal of the multiplier 30. The cut-off frequency of the low-pass filter 31 determines the width of the filter in the spectrum of the seismic signal. As the cut-off frequency is selected lower, the contribution of the environmental noise as a consequence of the input acceleration will decrease.

Since the word length of the signals Y(z) and T(z) is small, the realization of the digital circuit will be simple.
Claims

1. A geophone system, comprising a mechanical transducer and an electronic processing device, the mechanical transducer comprising an inertial mass and a force transducer, the inertial mass being adapted to be excited by an input acceleration signal and by the force transducer, the excitation being detected by a sensor element, said force transducer being controlled by the electronic processing device, which electronic processing device comprises an analog/digital converter being controlled by the sensor element, characterised in that the sensor element (4) detects the velocity of the inertial mass (2) and controls the analog/digital converter (8) by means of an amplifier (5) with a very high gain factor, in that the output of the analog/digital converter (8) is connected with the input of a digital/analog converter (11), and in that the output of this digital/analog converter (11) controls the force transducer (12).

2. The geophone system of claim 1, characterised in that the amplifier (5') has a low-pass characteristic, and in that the input thereof, apart from being connected with the velocity sensor element (4), is connected with the output of the digital/analog converter (11), in order to limit the control of the analog/digital converter (8) as a consequence of the offset of the amplifier (5'), and to suppress the quantization noise (Fig. 2).

3. The geophone system of claim 2, characterised in that the input of the amplifier (5'), apart from being connected with the sensor element (4), is connected with the output of the digital/analog converter (11'), in that the input of the digital/analog converter (11') is controlled by an inverter (9), and in that the inverter (9) also controls an arithmetic unit (10'), which, after a sample command from a clock (7), controls the other digital/analog converter (11), the arithmetic unit (10') integrating the digital signal (Fig. 3).

4. The geophone system of claims 1, 2 or 3, characterised in that a digital test signal T(z) is added in an adding
stage (10, 10') to the output signal of the analog/digital converter (8), the output of this adding stage (10, 10') being connected with the digital/analog converter (11), so as to allow to exert a force on the inertial mass (2) corresponding with this test signal and by means of the force transducer (12), the clock signal (7) for the analog/digital converter also acting as the clock signal for the test signal (Figs. 1, 2, 3).

5. A transducer for detecting mechanical vibrations, in particular seismic waves, comprising a coaxial permanent manetic assembly and a coaxial coil assembly comprising a sensing coil and a drive coil being arranged coaxially in a tubular outer pole shoe, one assembly being movable and the other one being stationary, springs being provided between both assemblies, characterised in that the magnet assembly consists of a permanent magnet (14) which, at both sides, is provided with two inner pole shoes (16), the drive coil (19) being arranged in the air-gap between one of the inner pole shoes (16) and the outer pole shoe (21), and the sensing coil (18) being provided in the air-gap between the other inner pole shoe (16) and the outer pole shoe (21), a compensation coil (20) being arranged outside the magnetic field of the magnet (14) and inside the outer pole shoe (21), all this in such a manner that the induction voltage induced as a consequence of the alternating flux produced by the drive coil (19) in the compensation coil (20) is substantially equal to the induction voltage induced as a consequence of the alternating flux in the sensing coil (18) (Fig. 5).

6. The transducer of claim 5, characterised in that the outer pole shoe (21') is mechanically rigidly connected with the inner pole shoe (16) by means of two spokes (23') (Fig. 6).

7. The transducer of claim 5 or 6, characterised in that the magnetic assembly comprises a third inner pole shoe (16) in front of the compensation coil (20), and is separated from the first inner pole shoe (16) by a non-magnetic interspace (15) (Figs. 5, 6).

8. The transducer of claim 5, 6 or 7, characterised
in that the inner pole shoes (16) are interconnected by means of an electrically conducting core (23) directed in the axial direction of the assembly (Figs. 5, 6).

9. A method for testing a geophone of claims 1, 2, 3 or 4, characterised in that a digital test signal is produced by reading a signal stored in a memory for controlling the geophone, a second test signal being produced by reading said memory with an n-times higher velocity, a digital multiplier multiplies the said second test signal with the output signal, the low-pass filter filtering the n-th harmonic distortion from the output signal of the multiplier (Fig. 7).
## INTERNATIONAL SEARCH REPORT

**International Application No.** PCT/NL 89/00063

### I. CLASSIFICATION OF SUBJECT MATTER

According to International Patent Classification (IPC) or to both National Classification and IPC:

**IPC**: G 01 V 1/18, G 01 H 11/02

### II. FIELDS SEARCHED

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

### III. DOCUMENTS CONSIDERED TO BE RELEVANT

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<td>Journal of Physics E Sci. Instrument., vol. 21, no. 8, 1988, IOP Publishing Ltd (Bristol, GB), Z. Yin et al.: &quot;A high-resolution wideband digital feedback system for seismometers&quot;, pages 748-752, see page 748, column 2, lines 12-23; page 749, column 1, lines 12-30; figures 1,3</td>
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<td>US, A, 3088062 (A.A. HUDIHAC) 30 April 1963, see column 12, lines 29-62</td>
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<td>US, A, 3429189 (H.F. KRABBE) 25 February 1969 cited in the application</td>
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### IV. CERTIFICATION

Date of the Actual Completion of the International Search: 13th November 1989

Date of Mailing of this International Search Report: 30. 11. 89

International Searching Authority: EUROPEAN PATENT OFFICE

Signature of Authorized Officer: F.M. VRIJDAG

Form PCT/ISA/210 (second sheet) (January 1985)
This annex lists the patent family members relating to the patent documents cited in the above-mentioned international search report. The members are as contained in the European Patent Office EDP file on 22/11/89. The European Patent Office is in no way liable for these particulars which are merely given for the purpose of information.

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