Investigation and Calibration of MEMS-Accelerometer for seismology and permanent reservoir monitoring

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Abstract

This paper investigates the behaviour of an accelerometer with very low frequencies (less than 20 Hz) for seismology and micro-seismic use. Teleseismic-signals and fluid transportation (cause of micro-cracks) in a carbon reservoir generate low signal-amplitudes and frequencies. Therefore is it most important to have sensors with high sensitivity.

The primary performance characteristics of acceleration measurement are sensitivity, dynamic range, signal-to-noise ratio (SNR), and frequency response.

To investigate these characteristics, we built a calibration system to generate a continuous sinusoidal acceleration. Seismic waves commonly used in seismology and passive reservoir monitoring have frequencies from 0.01Hz to 20Hz. Such deep frequencies are one of the major problems for accelerometers. Low frequencies produce a low acceleration and with that a low electrical signal. That low electrical signal limits the use of an accelerometer. Therefore the accelerometer has to be investigated up to which low frequencies it measures.

Introduction

Motivation

The rapid development in the micro technology is reached by a new combination of digital technique and mechanical components. That new combination is called MEMS (Micro-Electro-Mechanical-Systems) and means: the integration of mechanical elements, sensors and electronics on a common silicon substratum.

The MEMS accelerometer will represents the next generation in seismology. When compared the accelerometer to other wide bandwidth seismometer, the accelerometer improves the amplitude stability, frequency response, bandwidth, noise floor and the transverse sensitivity (K. E. Speller et al., 2004).

The response of the accelerometer is shown in *figure 1*. And in the upper diagram is the amplitude response and the lower diagram shows the phase shift. The *equation 1* is the transfer function of accelerometer and the *equation 2* of compared seismometer.

The accelerometers transfer function produces a highly under-damped 2nd order system. The amplitude A(ω) and the phase shift has a flat line below 6600 Hz.

The seismometer is a velocity sensing transducer and the transfer function looks like a high pass filter. The amplitude A(ω) and the phase shift has a low resonance structure and critical damping value around 0.707. Signals between 0 and ω_0 have poor amplitude and phase response. The seismometer response is shown in *figure 2*.

The transfer functions of accelerometer (eq.1) and seismometer (eq.2) are:

$$G_A(s) = \frac{K_P}{1 + 2 \cdot \frac{\delta}{\omega_0} + \left(\frac{1}{\omega_0}\right)^2 \cdot s^2} \quad (1) \qquad G_S(s) = \frac{K_P \cdot s^2}{1 + 2 \cdot \frac{\delta}{\omega_0} + \left(\frac{1}{\omega_0}\right)^2 \cdot s^2} \quad (2)$$

with ω_0 = resonance frequency
δ = damping
s = jωt
K_P = constant

Considering *figure 1* and *figure 2* the difference between the accelerometer and the seismometer is the pass band. The seismometer causes at the corner frequency ω_0 (resonance) a phase shift to 180 degree and an amplitude damping with -40dB/decade. Data collected with a seismometer have not a flat frequency response to low frequencies and requires a deconvolution process to correct amplitude and phase.

The accelerometer is flat below ω_0 and linear in phase and amplitude. That is the advantage and motivation to use an accelerometer in seismology!

The paper is separated in two parts. The first part shows how the calibration system (stimulus) works and how the transfer functions is resolved from the calibration system. In the second part, the paper shows the calibration data from an accelerometer.

Application of calibration systems

There are some reasons to calibrate sensors with a calibration system. One of them is the initial sensor calibration to verify performance against published specifications with respect to traceable, recognized measurement standards. Another one is the recalibration to ensure sensor integrity and to build confidence in measurement results.

Calibration is important to know the exact accelerometer sensitivity at various frequencies of interest. This calibration data can only be achieved through periodic calibration. And the periodic calibration is necessary to characterize accelerometer sensitivity and frequency response as well as ensure accelerometers integrity and detect possible damage. Calibration intervals are typically less than 12 months. This interval may be reduced based on usage, sensor integrity and environment.

Calibration system requirements

Any accelerometer (sensor) responds to its whole environment. Therefore the calibration system has a significant effect to the measurement accuracy. The major effects for low-frequency accelerations are: signal noise ratio (G. J. Stein, 2001), temperature and mounting surface strain (J. Wilson, 1999).

There are some causes to increase the *signal to noise ratio* and with that the dynamic range of accelerometers. If the noise of the calibration system exceeds the faint amplitude of the acceleration signal, however, the signal will not be measured.

In *fig. 3* you see the noise spectrum at the measure place. There is a short peak at 0.23 Hz and the noise is beginning to rise at 0.1 Hz. That limits the dynamic range of the calibration system and that should be considered. We have first tests made with a sand bed to reduce the low frequency noise amplitudes with more than -20dB.

The *operating temperature* affects the sensitivity of accelerometers. The MEMS accelerometer has a pyroelectric nature because of the piezoelectric materials. This effects increases with low-frequency, because low frequency means low acceleration. The internal components are differential thermal conductive and the thermal expansion (thermal deformation) of the proof mass as well as the path generates a vibration with low acceleration. Rapid temperature changes should be avoided. These vibrations can be reduced by providing a thermal shield or housing.

When the mounting surface of the *calibration systems is strained*, some strains are transmitted to the accelerometer and produce an acceleration output signal. This unpredictable strain output may be in or out of phase and is impossible to correct. To reduce this strain, we isolate the calibration system with rubber from the mounting surface strain.

Application of accelerometers

Accelerometers win more and more importance in geophysics, especially in seismology and passiv reservoir monitoring. They are built compactly, have great sensitiveness, are simply in handling, and use up only small electric current. Currently, the accelerometers measure the gravitation (in static case) on a millionth exactly.

The accelerometer examined here (Kistler Servok-Beam Type 8330A2.5), is a single axis capacitive forced feedback system with 1.3µg (<10 Hz) resolution. The mechanical system is a silicon proof mass and is between two silicon springs (upper and lower fixed electrodes). A capacitor integrated circuit measures the proof mass position and provides the feedback force (electrostatic field) to restore the proof mass to the center position. A compensation circuit generates an electrostatic feedback field with the voltage as measure signal. The electrostatic feedback field restores the proof mass to the center position, when the capacitances of both sides of the two silicon springs are equal.

The dynamic range of accelerometers is 80 dB or more. In this paper is the interest lies in the lower limit of accelerometer. The lower limit is not determined directly by the accelerometer, but by the electrical noise of connecting cables and amplifiers. Determination of the electric system noise level requires consideration of all noise sources, cables, and amplifiers.

Methods

This investigation shows, whether accelerometer is usable for seismology. The best way to calibrate an accelerometer is the knowledge of the relationship between its input (the ground acceleration) and its output (the electrical signal). The transfer function determines from the response by the known input signal.

The input to the accelerator is a continuous mechanically generated sinusoidal signal. The feature of this input is to check the steady state of the output, the presence of noise, permits the linearity of response, and enables phase relations between input and output. Both data (input and output) are measured with a data logger (24bit Sigma Delta AD Converter with 100Hz sample rate).

The stimulation is a motor with a rotation disc and a piston (*see fig. 4*). The piston moves the accelerometer forward and backward in a horizontal plane. The motor with the rotation disc is the heart of the stimulation. With the speed of the motor, the frequency of the stimulation is given. The rotation disc is needed to choose the maximum amplitude and with that the maximum acceleration. To this, the mounting of the piston bar can be moved by the centre of the rotation disc freely. When the radius and the frequency are given, the maximum acceleration can be determined by:

$$a = r \times \omega^2 \qquad (3)$$

r= distance from the piston bar to the centre of the rotation plate
ω= angle speed
f = frequency

The data evaluation is simple, if the mounting of the piston bar is in level with the piston bar (angle = 90° or 270°) the *equation 3* is solving to:

$$a = r \cdot \omega^2 \cdot \sin 90° = r \cdot \omega^2 \quad \text{with} \quad \omega = 2 \cdot \pi \cdot f \qquad (4)$$

The radius r and the angle speed are known precisely in that investigation. So the maximum acceleration can be determined easily. The radius of the disc is r = 2.5 cm and the speed angle depends on the frequency.

There is a light barrier to determine the phase shift. If the mounting of the piston bar passes a light barrier, a measuring system (data logger) will record an impulse. The reciprocal value of the time between two impulses is the frequency. But the accelerometer has its maximum or minimum amplitude 90° later as the impulse of the light barrier (*see fig. 4*)! That must be considered in the data processing.

The gravity is an incident signal, which has to be compensated. Therefore the accelerometer is placed in horizontal orientation, so that the output voltage has its minimum. In that case the sensor orientation is vertical to earth gravity.

Measurement

To calibrate the accelerometer, the earth gravity is a source of interference and must be compensated. The calibration system is horizontal aligned, with that the accelerometer moves horizontal and the earth gravity takes no effect (see *fig 4*). The accelerometer output signal is more or less zero Volts.

The motor rotational speed increase stepwise in time that at least 20 cycles are measured. That is necessary to correlate the acceleration signal with the calibration system function. Amplitude and phase are represented by the result of correlation (see *fig. 7*). The time delay between acceleration and the stimulus from the calibration system is a function of the frequency and the damping of the accelerometer.

In *figure 5* we see filter processed data from the acceleration calibration. Due to the fact that the noise increases at 0.1 Hz we filtered the acceleration signal with 0.01Hz high pass filter. Depending on calibration frequency we low pass filter the acceleration signal between 10 Hz to 1 Hz. At *figure 5* the head plot shows the acceleration signal unprocessed in Volt. In the middle plot we see the processed acceleration signal also in Volt. The lower plot shows the generated sinusoidal signal from the light barrier impulse signal. With *equation 4* the acceleration is: 1.0667 m/s^2.

The *figure 6* represents processed acceleration data with 0.103 Hz. In the upper plot as technical control we see the unprocessed data. The amplitude from the accelerometer is more or less 0.002 Volt and the signal to noise ratio decrease. The middle plot shows the processed data with amplitude in Volt. And the lower plot shows the generated sinusoidal acceleration. The amplitude is 0.0098 m/s^2.

Results

The Bode diagram (see *fig. 7*) is prepared from the calibration measurements. Amplitude response and phase shift are plotted dependence frequency. Because of the noise the acceleration is measured only to 0.1 Hz. The amplitude response is a flat line and the phase shift is nearly zero. From the accelerometer data sheet the amplitude is specified to -16 dB (±5%). In *figure 7* the upper plot shows the amplitude response from 0.1 Hz to 1 Hz as a flat line with -15.6 dB. The phase shift is showed in the lower plot and is like the amplitude a flat line with more or less 0°. With that, the phase angle is proportional to frequency, which results in a constant time delay for tested frequencies. This is important in the case of seismic waves, which are made up of many frequencies. The shape of the waveform would not be maintained if there are phase (time delay) differences between higher and lower frequencies.

In summery the frequency response for amplitude and phase shift is in 5% range. The lower dynamic limit of the accelerometer is not reached. Only the noise floor limits the calibration.

Conclusion

This investigation has showed that accelerometers are principle useable for seismology. The measure frequency is between 0.1 Hz and 20 Hz without amplitude damping and phase shift. Lower frequencies are reduced by the noise floor and limit the dynamic range. It seems, that the lower boundary not determine directly by the accelerometer, but from the electrical noise (connecting cables, filters and AD converter).

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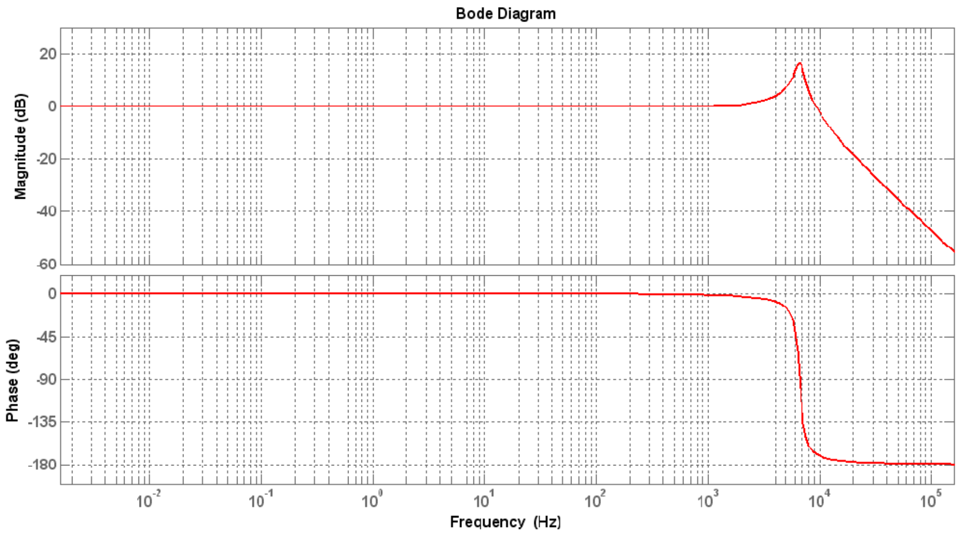

Fig. 1 Bode diagram accelerometer, resonance frequency is 6600 Hz

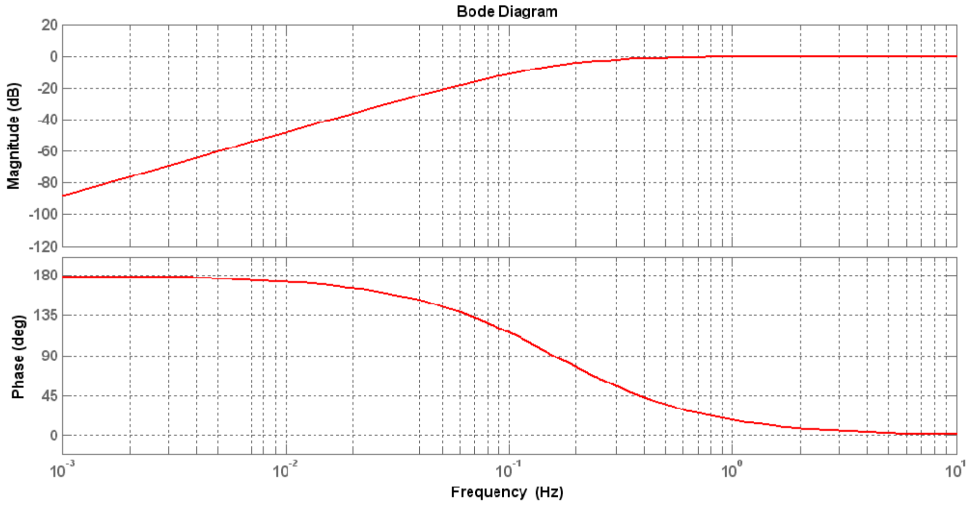

Fig. 2 Bode diagram seismometer, resonance frequency is 1 Hz

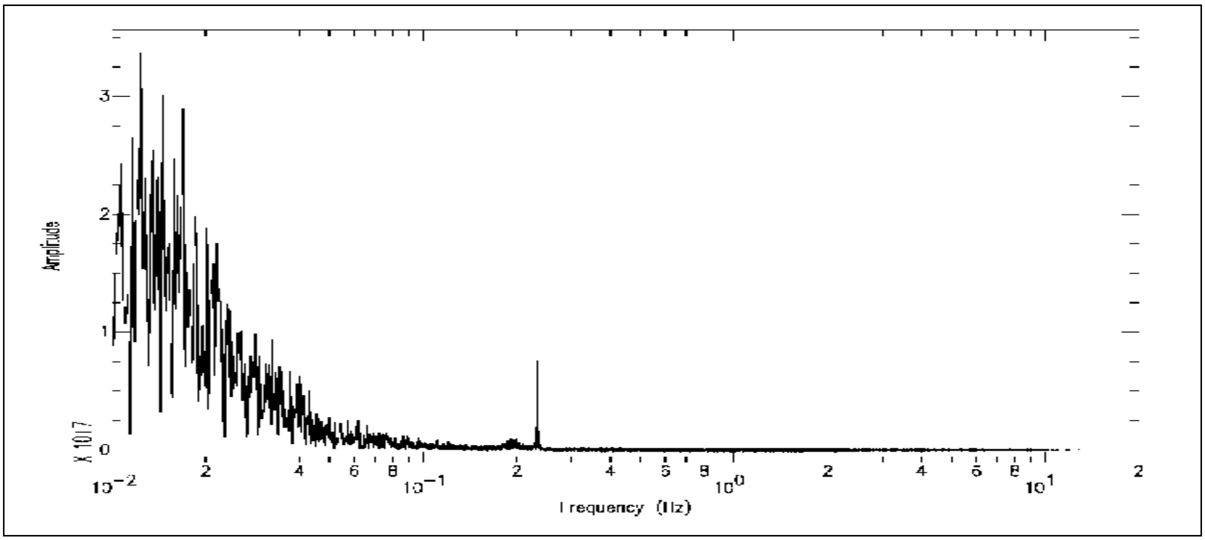

Fig. 3 Amplitude spectrum of the measurement place.

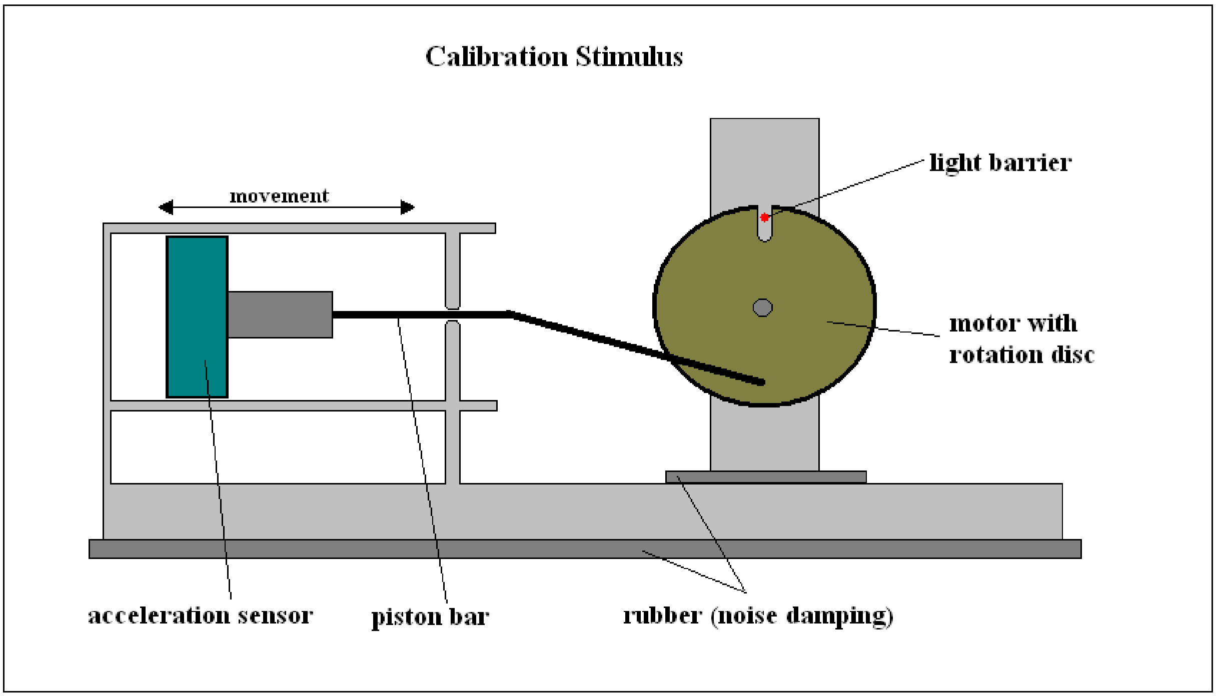

Fig. 4 Sketch of the calibration stimulus

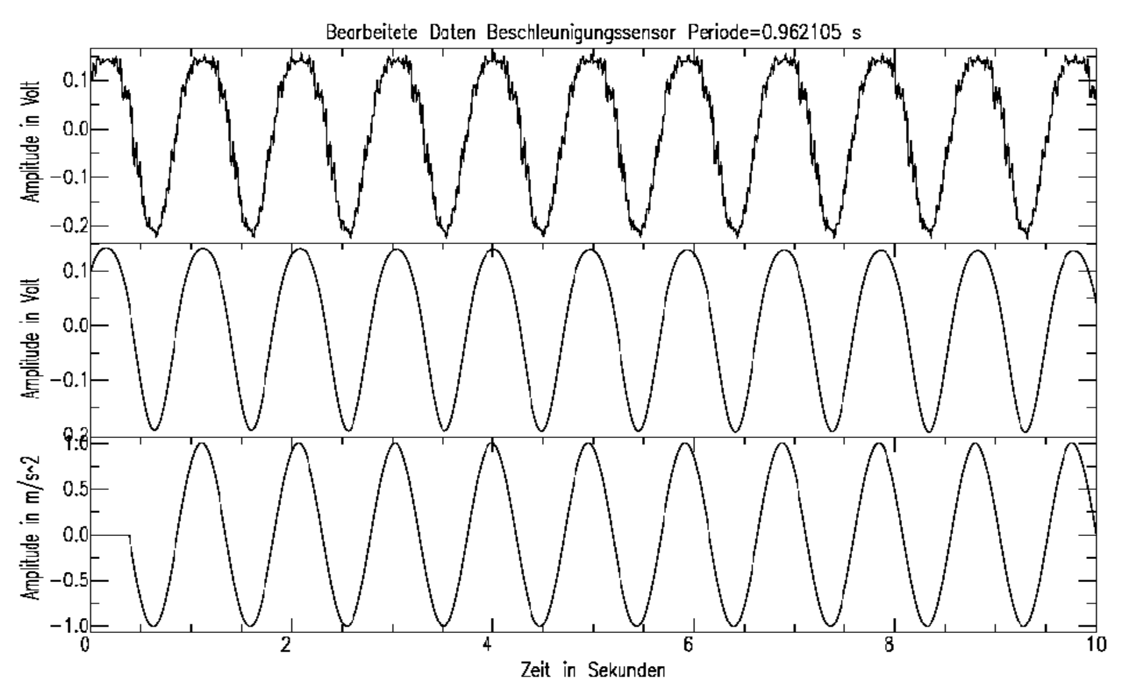

Fig. 5 *acceleration measurements. Stimulus frequency is f=1.04 Hz*

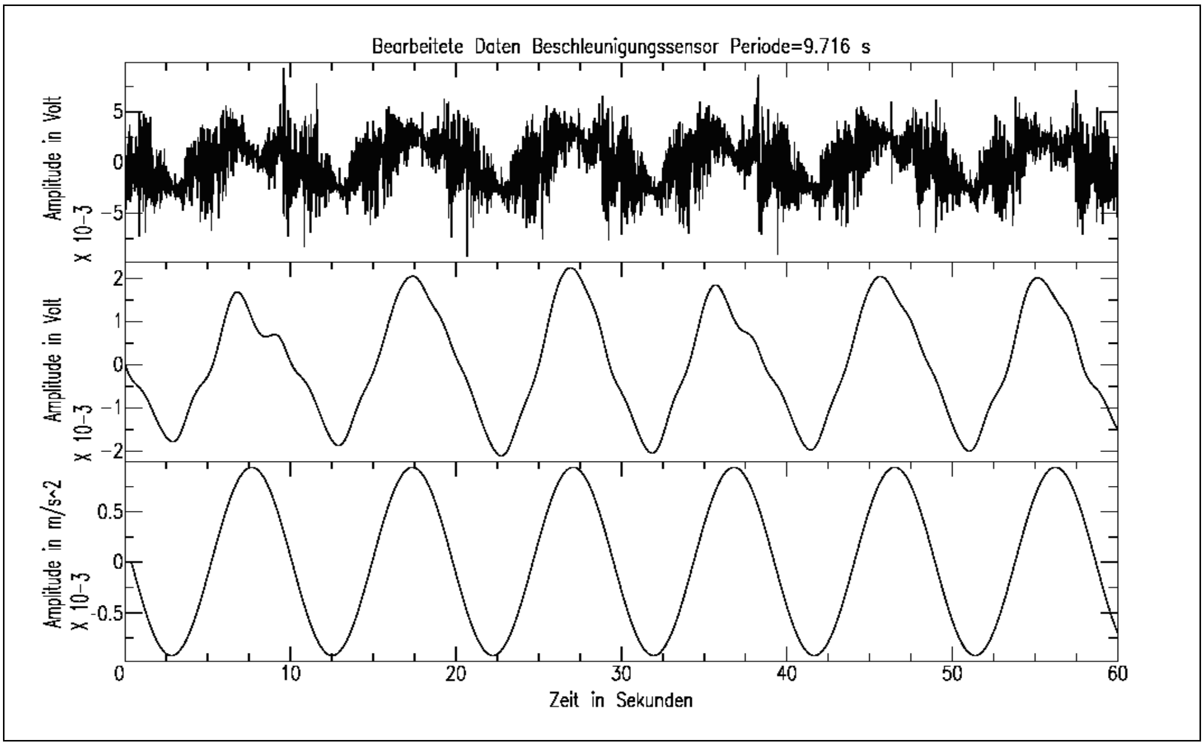

Fig. 6

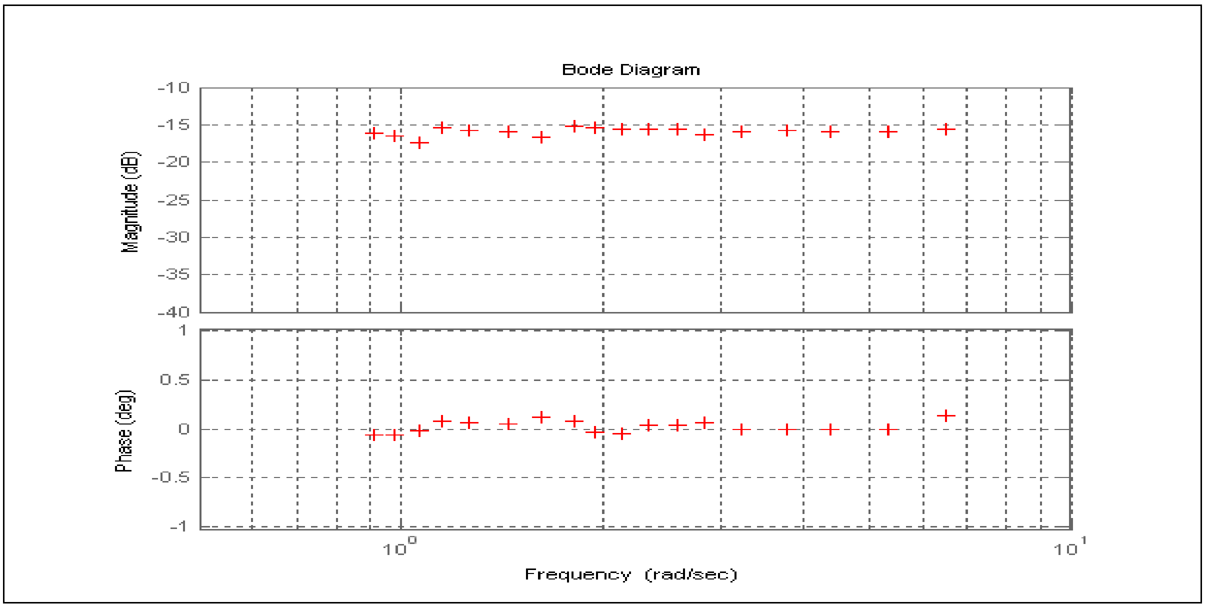
Bode Diagram
Magnitude (dB)
-10
-15
-20
-25
-30
-35
-40
Phase (deg)
1
0.5
0
-0.5
-1
10^0
10^1
Frequency (rad/sec)

Fig. 7