J. Geophys. 41, 303—310, 1975

An Electronic Filter and Damping System for the Askania Borehole Tiltmeter

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Received June 25, 1974; Revised Version January 23, 1975

Abstract. A Butterworth-Bessel low-pass filter is described which filters the output signal of the Askania borehole tiltmeter. The frequency and time-domain properties of the filter characteristics have been adapted optimally for using the tiltmeter as an earth tide recording instrument. Furthermore, a damping system of the instrument is described. This device prevents the linear range of the electronic recording system from being exceeded under extreme conditions, e.g. strong microseisms. Due to the improvements achieved the accuracy of the records has been raised substantially.

Key words: Tilt and Solid Earth Tidal Measurements – Borehole Tiltmeter – Vertical Pendulum – Electronic Filters.

1. Introduction

The Askania borehole tiltmeter (vertical pendulum) is an instrument which is suitable for recording low-frequency tilts and horizontal accelerations. For the reduction of surface influences, especially meteorological effects, it is installed in 30 m deep boreholes (Flach and Rosenbach, 1971). In common with nearly all recordings of geophysical data, the problem has to be considered that the atcual signal, e.g. tides, is accompanied by undesirable noise, e.g. microseisms. If the noise covers another frequency range than the signal its separation and elimination is practicable. In the present case low-pass filtering must be used, since the noise frequencies (microseisms, natural period of the pendulum) are much higher than the signal frequencies (tides). Originally a passive two-pole low-pass filter has been used by the manufacturer. But for the following reasons, this type of filter does not meet the requirements based on the present state of electronics:

1. Passive low-pass filters with very low cutoff frequencies of 4×10^{-4} Hz can technically only be realized with electrolytic capacitors depending to a high degree on time, temperature and input voltage. Furthermore, passive networks are not independent of load.

2. The step response of such a filter is very poor because of the high time lag of 40 min. This property particularly causes problems of the transfer of the calibration pulse (Flach, Jentzsch, Rosenbach and Wilhelm, 1971).

An active filtering and damping system will be described in the following. In the case of tidal recordings it mainly filters the noise (microseisms, natural period of the pendulum) superimposed on the signal and is optimally adjusted to the conditions at the station Zellerfeld-Mühlenhöhe (51.82 °N, 10.34 °E).

2. *Specifications of the Filter*

The signal generated by the recording system of the tiltmeter contains frequencies between 0 Hz and the natural frequency of the pendulum (0.7 Hz). Above the tidal frequencies it mainly consists of the frequencies of the oceanic microseisms (0.15—0.25 Hz) and the natural frequency of the measuring pendulum (0.7 Hz). The maximum amplitude of the microseisms at the station Zellerfeld-Mühlenhöhe is about 30 mV_{pp} at 0.15 Hz, corresponding to the 1.5-fold tidal maximum amplitude.

A suitable low-pass filter has to attenuate the amplitudes of the microseisms in such a way, that they do not appear in the tidal records any longer. In order to be sure that the microseisms under no circumstances affect the recordings a damping of —80 dB is necessary. Such an attenuation can be realized by filters of different constructions and specifications. The following conditions should however be complied with as far as possible.

(a) flat amplitude response in the band-pass of the filter,

(b) high attenuation beyond the cutoff frequency,

(c) small phase shift at tidal frequencies,

(d) good step response properties,

(e) high input impedance, low output impedance,

(f) simple design,

(g) good possibility of realization with regard to the properties of the construction elements.

From these conditions it follows that only active filters are in consideration, since (e) and (d) require the use of amplifiers.

2.1. Choice of Filter Type

Active filters allow complicated amplitude and phase responses which are optimally designed with regard to different aspects (Tietze and Schenk, 1971). The most important filter types are Butterworth, Bessel and Teschebyscheff. Conditions (a), (b) and (c), for example, are very well met by a Butterworth filter, while for condition (d) the Bessel filter is particularly suitable. Conditions (e), (f) and (g) apply to all active filters in like manner and are of no importance in selecting the type of filter.

A Butterworth filter however is ruled out for filtering the signal in question because of its disadvantageous step response.

During the calibration of the tiltmeter by the ball calibration method, square wave impulses are superimposed on the tidal signal. These are due to the shift of a small ball inside the measuring pendulum by an exactly defined amount (Jacoby, 1966). As the accuracy of the calibration strongly depends on the number of calibration pulses in a fixed time interval (Flach, Jentzsch, Rosenbach and Wilhelm, 1971), it is desirable to carry out the calibration pulses as quickly as possible (Große-Brauckmann, 1973). As a fast step response allows more calibration cycles in a fixed time interval a Butterworth-Bessel low-pass filter was chosen. This is a compromise between the good amplitude response of the Butterworth filter and the advantageous step response of the Bessel filter. The poles of such a filter are located in the complex frequency plane between those of the Butterworth and Bessel filters (Al Nasser, 1972).

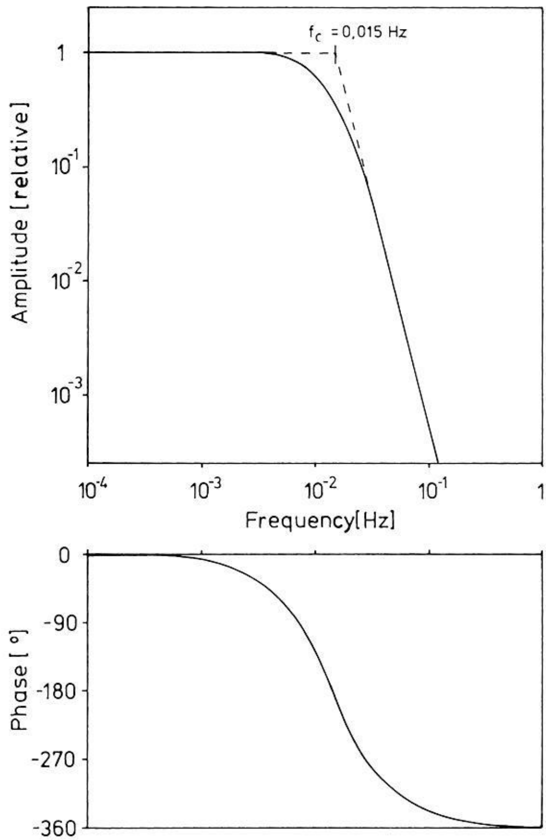

Fig. 1. Frequency response of the four-pole Butterworth-Bessel low-pass filter (amplitude above, phase below). Cutoff frequency 0.015 Hz

For the required damping of —80 dB at 0.15 Hz a four-pole Butterworth-Bessel low-pass was chosen. The number of poles n of a filter determines the attenuation of the gain m^+ beyond the cutoff frequency f_c according to

$$m^+ = -n\ 20\ \mathrm{dB/decade\ for}\ f > f_c \tag{1}$$

The less the number of poles of the filter, the lower must be its cutoff frequency to achieve the same attenuation at a fixed frequency.

A four-pole filter is constructed by using 2 two-pole filter elements in series. The capacitances and resistances can easily be calculated by the aid of tables (Al Nasser, 1972).

2.2. Characteristics of the Filter

In case of high resistance signal sources it is advisable to connect the filter with a differential amplifier in series, since otherwise the output resistance of the signal source is added to the input resistance of the filter circuit and the filter characteristic will be changed. Furthermore, with the amplifier in series an additional gain can easily be obtained. A further advantage of the differential amplifier is the suppression of common mode noise which is capacitively superimposed on circuits.

A graph of the amplitude and phase responses is given in Fig. 1.

The step response of the filter shows an overshoot of 3%. After 130 sec the deviation from full deflection lies within 0.1%.

2.3. Test of the Filter

A critical point of active filters is the constancy of zero setting of the output voltage depending on the offset voltage drift of the operational amplifiers used in filter circuits. In Table 1 all data of the filter are given with regard to the drift and noise properties of the operational amplifiers.

Table 1. Drift and noise properties of the filter

Zero drift (dependent on time)	Zero drift (dependent on temperature)	Noise (0.001—10 Hz
4 μV / day	2 μV / degree centigrade	1 μV_{pp}

As 1 bit of the digital recording system represents a voltage of 50 μV, it is obvious that these values do not affect the accuracy of the records. The increase of the zero drift is non-linear in time. After x days the total drift is about $\sqrt{x}$ times the drift per day. This dependence was empirically derived from long-term measurements (Analog Devices, 1971).

Fig. 2 shows a record of 2 days. For a better control two identical filters have been connected in parallel with the same channel of the borehole tiltmeter. These have now been operating successfully for more than 18 months. Besides tidal waves surface waves of a distant earthquake can be recognized in the record. As these waves can have periods of some 100 sec and very large amplitudes, they are not suppressed by the low-pass filters.

3. Damping of the Pendulum by an Electronic Feedback System

3.1. Mechanical Properties of the Pendulum

Examinations of the mechanical behaviour of the Askania borehole tiltmeter revealed a very small damping of the pendulum, the damping factor being about 0.01. Strong microseisms in the frequency range of the pendulum's natural frequency of 0.7 Hz result in resonant oscillations and therefore the unfiltered signal shows very large amplitudes. In extreme cases the amplitudes may exceed the linear amplification range of the recording system. Then the integration of the falsified signal by the lowpass filter yields a measuring signal which is distorted considerably without any possibility of recognizing this distortion afterwards.

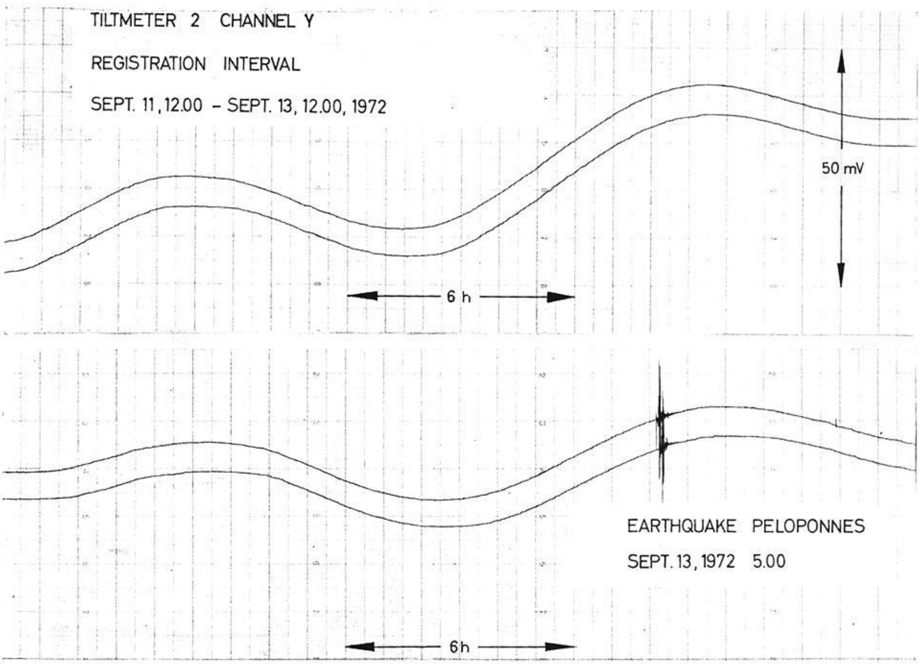

Fig. 2. Original record of 2 days; synchronous filtering of the same signal component with two identical filters in parallel.
Time shift of the traces due to the pen position of the recorder: 3 min
Continuous record from 11 Sept, 1972 / 12 00 EMT to 13 Sept., 1972 / 12 00 EMT

Short-time accelerations which may occur in seismic areas are able to overexcite the undamped measuring system as well. However, it is very important to get correct recordings during and immediately after earthquakes in order to detect possible sudden tilts of the earth's crust due to the earthquake mechanism.

The reasons mentioned above speak for a stronger damping of the pendulum. Two methods of damping can be considered:

mechanical damping by dipping the pendulum in a viscous fluid,

damping by electronic feedback of the pendulum's movement.

Fluid damping has not been planned by the constructors of the tiltmeter and would only be realizable by fundamental alterations of the instrument.

3.2. Damping by Differentiating Feedback

Damping by electronic feedback can be achieved by translatory forces at the pendulum's lower end which are proportional, but with a phase shift of 180°, to the velocity of the pendulum. Such forces can be generated by the device provided for continuous calibration of the tiltmeter (Jacoby, 1966). This device consists of a small permanent magnet mounted on the pendulum's lower end and a Helmholtz coil attached to the pendulum carrier. A current through the coil creates a homogeneous magnetic field which produces a certain force upon the pendulum. The strength of the magnetic field and consequently the deflection of the pendulum is proportional

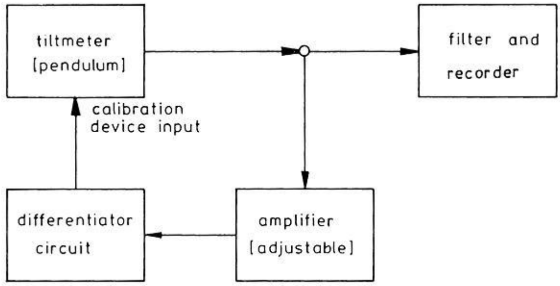

Fig. 3. Block diagram of the complete damping system

to the current in the coil. By the aid of a suitable feedback circuit and the calibration device just described a damping system was built which makes possible damping factors up to $\alpha \approx 1$ without any reconstruction of the tiltmeter.

The output voltage of the recording system is proportional to the angular deflection of the pendulum. A signal corresponding to the velocity of the pendulum can be obtained by differentiating this voltage with respect to time. The operation d/dt is achieved by an electronical differentiator, which contains operational amplifiers for the improvement of the differentiating properties of this circuit. In order to adjust the gain of the feedback system G_F a preamplifier is connected in series with the differentiator circuit. A block diagram of the complete damping system is shown in Fig. 3.

The feedback is applied to both components X and Y of the pendulum's movements in order to achieve a total damping of the tiltmeter.

3.3. Samples of Results

Investigations of the pendulum showed that by the aid of the feedback circuit damping coefficients up to $\alpha = 1$ can be realized depending on the gain G_F of the feedback voltage. As the gain of the differentiator decreases at low frequencies by —20 dB/dec G_F is always related to 1 Hz. The relation between the damping coefficient and G_F is linear but the mechanical damping α_M of the pendulum has to be added to the damping by feedback, i.e.

$$\alpha = \alpha_F + \alpha_M \tag{2}$$

with $\alpha_F = D\, G_F$ $\qquad D = \text{const} = 0.031$

and $\alpha_M = 0.01$

In practice it is most advantageous to use gains of $G_F \approx 23$ dB which result in a damping coefficient of $\alpha = 0.5$ so that at 0.7 Hz the resonant increase of the pendulum's amplitude is about 1.15 (compared with a resonant increase of 55 of the undamped pendulum). An undesired heating of the Helmholtz coils is largely avoided in this case. The loss of heat is about 10 μW as an average while the preamplifiers of the capacitive transducer system have a power loss of 60 mW. These values demonstrate the small contribution of the feedback system to the total power loss.

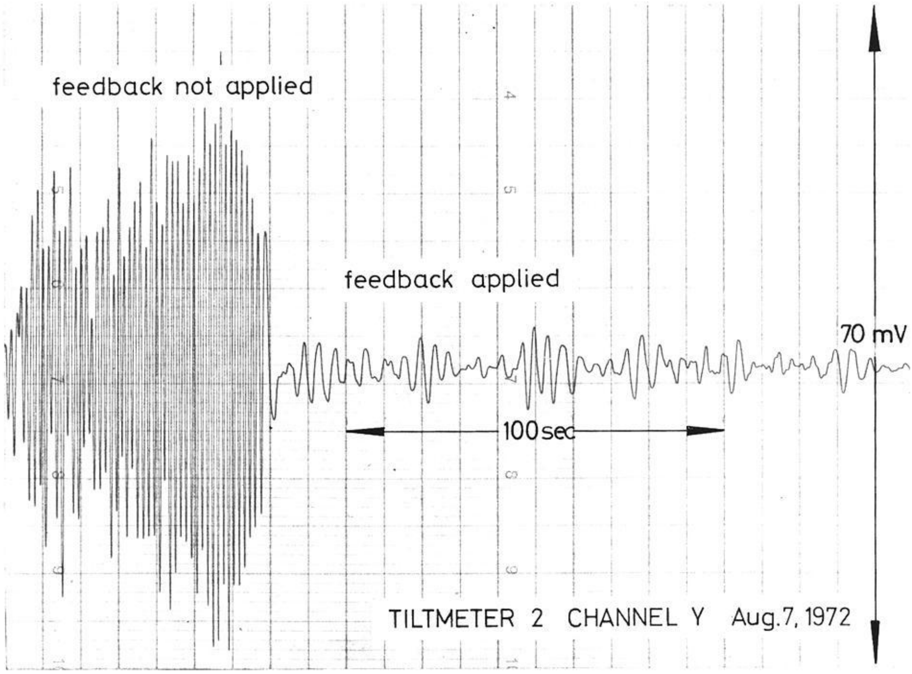

Fig. 4. Unfiltered signal without and with damping of the measuring pendulum

If the feedback voltage is increased very much, i.e. the gain G_F at 1 Hz is higher than 30 dB, resonant rises of the pendulum appear. They are caused by the non-ideal features of the differentiator circuit and a certain amount of cross coupling between both components.

In Fig. 4 the effect of the damping system is shown by means of an original record of the unfiltered signal. Without feedback the signal contains amplitudes up to 70 mV_{pp} mainly caused by the natural oscillations of the pendulum. After the damping device has been applied, the amplitudes are greatly reduced to about 10 mV_{pp}.

The influence of the damping system on tidal amplitudes is very small. Due to the small gain of the differentiator circuit at tidal frequencies (—93 dB compared with the gain at 1 Hz) this influence is less than 0.005% of the maximum semidiurnal tides at the station Zellerfeld-Mühlenhöhe.

A long-term record of the constancy of the zero setting of the damping circuit revealed a drift of 14 μV in 16 days. Such a direct voltage is superimposed on the feedback voltage and causes a deflection of the pendulum of 0.006% of the maximum tides. Thus a serious effect of this drift on the long-term stability of the tiltmeter can be excluded.

4. *Conclusions*

By means of modern operational amplifiers it is possible to construct active filters which are substantially superior to the passive filters originally used by the manufacturer of the Askania borehole tiltmeter. This superiority covers the frequency response as well as the long-term and temperature stability.

Furthermore, the Butterworth-Bessel filters with a cutoff frequency $f_c = 0.015$ Hz especially reconciled with the requirements of the recording system of the Askania borehole tiltmeter enable a more accurate performance of the ball calibration (Große-Brauckmann, 1973).

The electronic damping device makes it possible to operate the tiltmeter even in regions of strong microseisms since it prevents resonant oscillations which could exceed the linear range of the recording system. By a special design of the differentiator circuit of the damping device an undesirable heating of the Helmholtz coils due to high-frequency influences is avoided. The damping device has no significant effect on tidal recordings.

Acknowledgement. We wish to thank Prof. Dr.-Ing. Rosenbach for the encouragement to our work. Furthermore, we are grateful to the German Research Society (Deutsche Forschungsgemeinschaft) for the financial support of the measurements with the Askania borehole tiltmeter.

References

Al-Nasser. F : Tables shorten design time for active filters. Electronics *23*, 113—118, 1972

Analog Devices: Long-term drift measurements on op amps. Analog Dialogue *5*, 13, 1971

Flach, D., Jentzsch, G., Rosenbach, O., Wilhelm, H.: Ball-calibration of the Askania borehole tiltmeter (Earth tide pendulum). Z. Geophys. *38*, 1005—1011, 1971

Flach, D., Rosenbach, O.: Der Askania Bohrloch-Neigungsmesser (Gezeitenpendel) nach A. Graf auf der Test-Station Zellerfeld-Mühlenhöhe. Bull. Inform. Marèes Terrestres *60*, 2934—2943, 1971

Große-Brauckmann, W.: High precision ball calibration of the Askania borehole tiltmeter (Earth tide pendulum). 7th Int. Symp. on Earth Tides, Sopron (Hungary) 1973

Jacoby, H.-D.: Das neue Bohrloch-Gezeitenpendel nach Graf. Askania Warte *67*, 12—17, 1966

Tietze, U., Schenk, C.: Halbleiter-Schaltungstechnik. Berlin-Heidelberg-New York: Springer 1971

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