SENSITIVITY OF BROADBAND SEISMIC INSTRUMENT PARAMETERS TO ENVIRONMENT

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Abstract. The principal difficulty in the way of designing effective broadband seismic instruments, including tiltmeters, consists in noise that is frequently not of seismic origin and whose effects on the instrument are increasing as the instrument's response function is expanded to longer periods. Environmental sensitivity is sensitivity of instrument parameters to its environment (pressure changes, temperature changes, magnetic field variations, etc.). For many years authors investigated these effects that changes in external conditions have on the operation of broadband devices and on their output signal. These studies provide a comprehensive analysis of diverse methods for noise suppression. Authors investigated effects such as changes of temperature, air pressure, magnetic field, humidity, snow cover and groundwater table, examined the effects of thunderstorms, vibration, air currents, gravitational excitation, and so on. We examined the design elements of instruments, determined the effects of inelastic spring strain, Brownian motion under the instrument case, verified the sensitivity of the broadband instrument's response function to variations in the parameters of the elements around nominal values, and so on. Some interesting findings and recommendations are presented.

INTRODUCTION

To solve a wide range of scientific and applied tasks in seismology, such as studying Earth's free oscillations and slips, monitoring of nuclear explosions and the like, the necessity often appears in a large amount of seismic data with a high signal-to-noise ratio at long periods. It includes not only knowledge of the values of the Earth's surface motion along three axes, but also the values of tilt or rotations of the surface.

The development of a new broadband seismic instrument (BSI) should begin with preliminary theoretical study that includes, first of all, the investigation of noise which is expected to be generated by the device under the action of fluctuations of environmental factors. This noise limits a frequency band of devices from the long-period side and their dynamic range from below.

Recent tomographic studies using ambient seismic noise require the self-noise of seismic instruments to be below that of the Earth's ambient background noise, because as they use Earth noise as the seismic signal.

Development of such BSI implies the solution of several complicated technical problems. The primary attention is paid by world seismology to practical solution of this problem, providing by new technologies in seismometry, electronics, and computers.

Experimental determination of the noise characteristics of the existing BSI is limited by a microseism level in the places where the devices are installed. In view of this, the theoretical study of noise generating factors and channels of noise generation is of special importance. One of our tasks was to develop a set of recommendations that may be used by seismometer manufacturers and instrumentation users.

SIGNIFICANT EFFECT

In the literature there is an unanimous consensus on the meteorological origin of long-term ambient noise disturbances. To theoretically calculate the self-noise of the sensor manufacturers use the value of Brownian noise. However, it is well known that the main practical problems in long period instruments arise from thermal, magnetic field, pressure effects in the mechanical system and the mechanical instability of the overall construction.

One of the main noise generating factors in the broadband seismometers is the ambient temperature variations. At the ambient temperature fluctuations, almost all physical and geometrical characteristics of a device vary.

The leading role is played usually by influence of temperature changes on the crossed leaf rotary flexural system. The crossed leaf rotary flexure is simply two or more cantilever flexures mounted at right angles to each other. Generated noise is highly dependent on the leaves initial parasitic bending (Fig.1):

$$z_{\mathrm{E}} = \frac{l_{\mathrm{S}} E_0 b h^3}{48\pi^2 f^2 K q} \varphi_0 \cdot \alpha_{\mathrm{E}} \Delta t,$$

where z_{E} is the equivalent moving of soil, K and l_{S} are mass moment of inertia of the seismometer pendulum and its effective length, E_0 is the elastic modulus of the material of the leaf flexure at the mean temperature, α_{E} is thermoelastic coefficient, b is the total width of the blades and h is their thickness, q is the length of the leaf, φ_0 is the initial parasitic bending and Δt is the amplitude of temperature fluctuations at a frequency f.

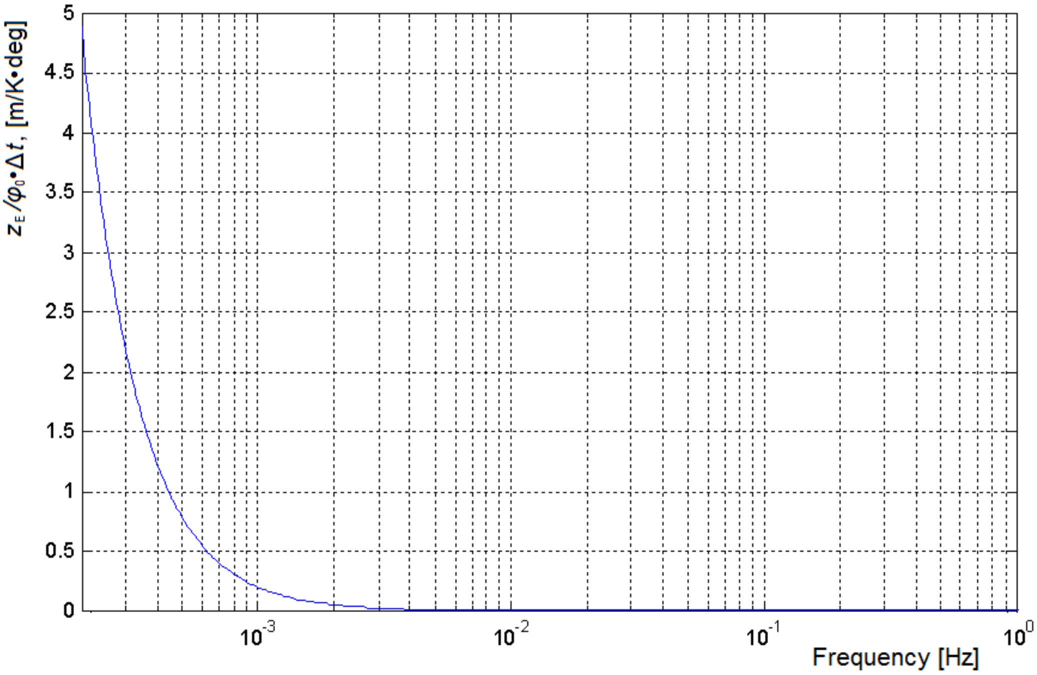


Fig. 1. An example of constructing of the noise transfer function generated by the crossed leaf rotary flexure, in relation to the amplitude of ambient temperature changes and the initial bending angle (for the seismometer SK-1 [1]).

The temperature strongly affects the vertical pendulum spring too. If to use a zero-length spring,

$$\frac{z_{\mathrm{E}}}{\Delta t} = \frac{g}{4\pi^2 f^2}\left(2\alpha_1 + \alpha_2 + \alpha_{\mathrm{E}}\right),$$

where coefficient of thermal linear expansion for spring is α_1 and for material of the pendulum and frame is α_2, g is acceleration of gravity, α_{E} is the thermoelastic coefficient of the spring. Note that the thermal noise depends only on the applied materials and does not depend on the design.

One kind of temperature-induced noise is the change in the linear dimensions of the instrument's elements, which are recorded by the seismic sensor as ground motion. We propose estimates which can help toward, first, determining the elements that are the most sensitive to ambient temperature variations, that is, those causing the greatest noise in records and, secondly, determining the level of noise due to the entire set of the elements. We obtained a general expression for frequency-dependent apparent ground motion displacement in relation to design dimensions and the materials used to build the instrument (Fig.2).

$$\frac{z_{\mathrm{E}}}{A} = \sqrt{\left(\sum_{j=1}^{m} \frac{L_j \alpha_j \cos\varphi_j}{\sqrt{1+4\pi^2\lambda_j^2 f^2}}\right)^2 + \left(\sum_{j=1}^{m} \frac{L_j \alpha_j \sin\varphi_j}{\sqrt{1+4\pi^2\lambda_j^2 f^2}}\right)^2},$$

where external temperature amplitude at frequency f is A, conditional coefficient of thermal inertia of the j-th element is λ_j, phase shift relative to the actual temperature is $\varphi_j = -\mathrm{arctg}\, k_j$, and relative coefficient of thermal inertia to changes in the temperature is $k_j = 2\pi f \lambda_j$ [2].

Effect of temperature on other elements of the broadband seismic instruments (BSI) is smaller, although it should be taken into account when designing devices. The more carefully the device will be protected from changes in ambient temperature, the higher will be its time constant, the better. If the diurnal temperature cycle in the hardware chamber exceeds 1°C, it is expedient to apply additional passive or active thermostats (fig.3) or temperature compensator.

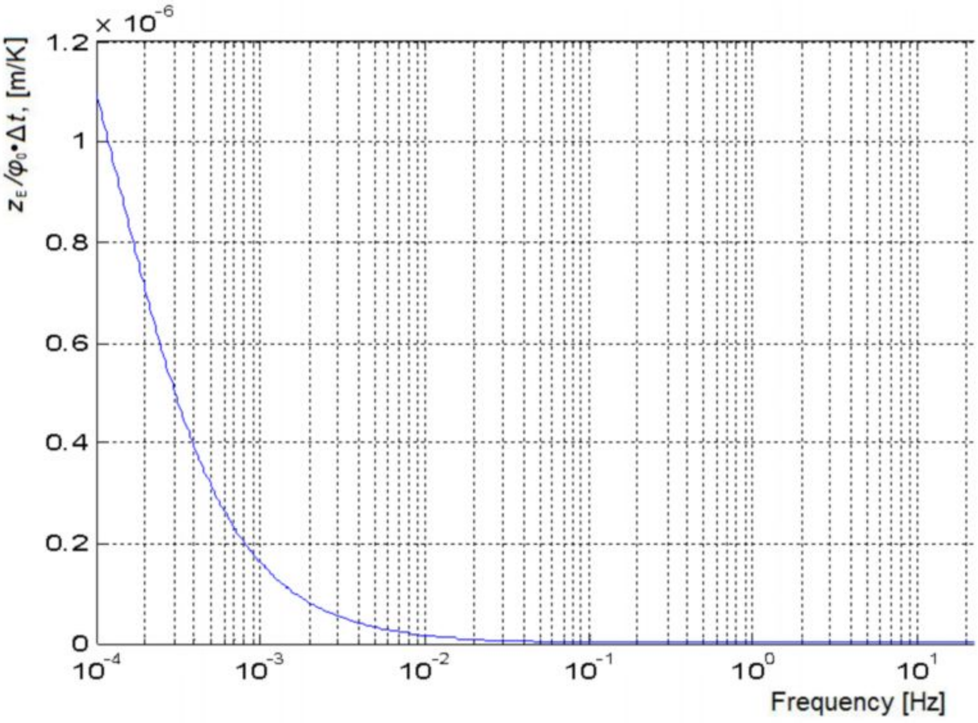


Fig. 2. An example of constructing of the noise transfer function generated by the temperature variation of the linear dimensions, in relation to the amplitude of ambient temperature changes (for the seismometer SK-1).

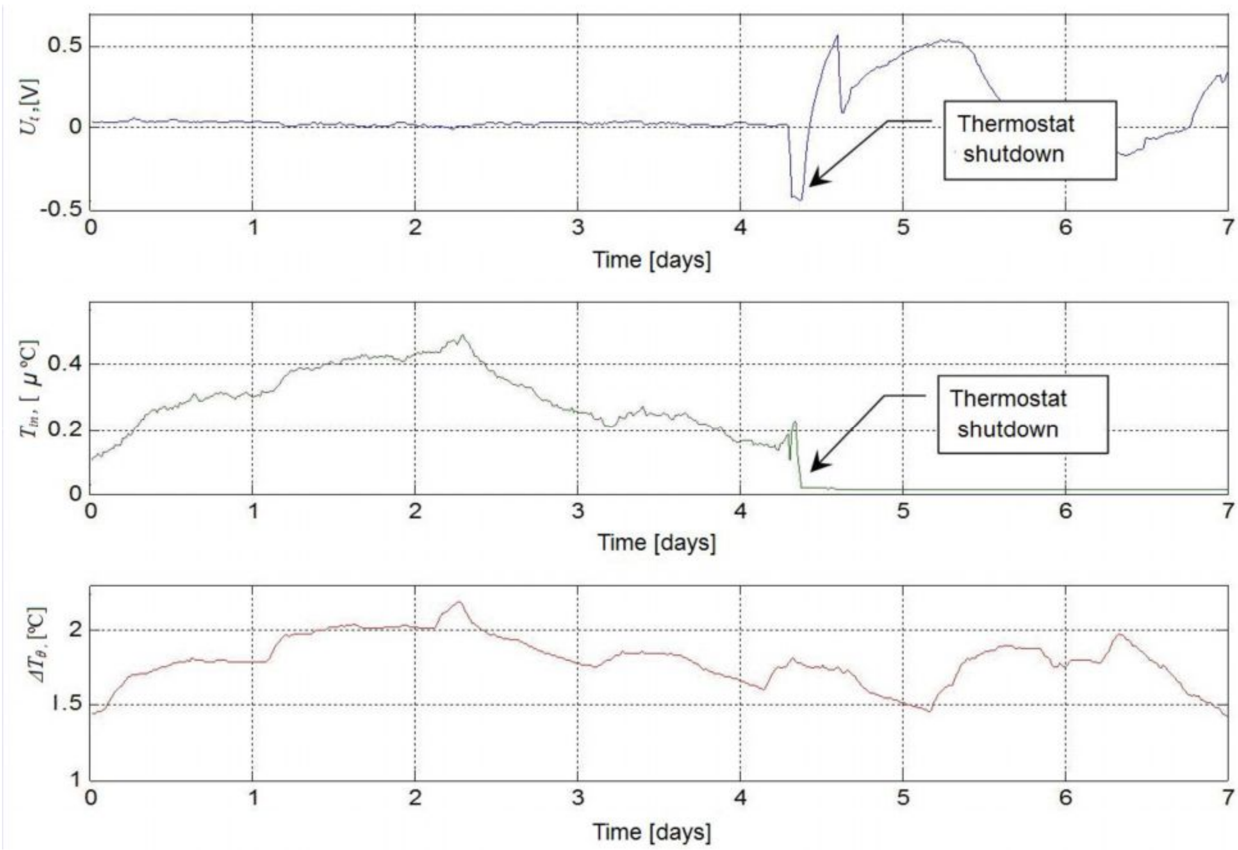


Fig.3. The suppression of thermal noise the KST-1 gyrotiltmeter with active thermostat [3]
ΔT_θ - changing the temperature of the environment,
ΔT_{in} - temperature variations in the internal volume,
Ut – output tiltmeter.

Barometric pressure is very powerful factor acting onto BSI too. The temperature inside the device is varying due to the adiabatic process of changing its volume; buoyancy force is changing; and the instrument housing is being deformed. The noise level depends on the amplitude of pressure fluctuations and the structural stiffness.

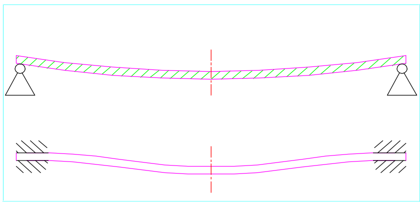
Predetermining maximum limit of temperature changes Δt, we can easily go over to admissible change of volume $\Delta t/t_0 = 1 - 1/(1+\Delta V/V)^{(\gamma - 1)}$, where specific heats ratio of air $\gamma = 1{,}403$; t_0 is integral temperature; ΔV is the changing of housing volume V. After that we can calculate a design of the instrument housing using standard methods of the theory of elasticity and the strength of materials or the finite element method. It is rather simple, as we know possible variations of pressure.

Similarly, we can reduce the noise caused by changes in Archimedes buoyant force. If we know the uncompensated volume moment M_V of a vertical seismometer pendulum and the allowable level of noise, we can calculate the allowable variation of pressure ΔP_{MAX} inside the instrument. Taking the maximum permissible error for long periods of 10^{-5} m, and assuming that pressure fluctuations are harmonic processes, we have:

$$\Delta P_{MAX} = 3{,}94 \cdot 10^{-4} \frac{KP_0}{M_V l_S g \rho T^2},$$

where K and l_S are mass moment of inertia of the pendulum and its effective length, T is the period of the pressure oscillation, ρ is the air density and P_0 is the initial barometric pressure. Using this value we can construct the housing by the same way.

It is the most difficult to consider displacement and deflection (tilt) of elements of the device because of case deformation. This problem of estimating the displacement and tilt can be solved analytically or numerically [4]. In most cases, we may assume that the true deformation of the basis of the device represents something an average between two models which presented in fig. 4.



a - plate edges are pin-ended

b - plate is with stiffened edges

Fig. 4. Deformation of the device basis of various models.

According to the first model the vertical deformation is

$$w = \frac{\Delta P\left(l_K^2 - r^2\right)}{64D}\left[\frac{5+\mu}{1+\mu} l_K^2 - r^2\right],$$

to the second is

$$w = \frac{\Delta P\left(l_K^2 - r^2\right)^2}{64D},$$

where ΔP is the difference between external and internal pressures, r is the distance from the plate center, l_K is the plate radius, μ is the Poisson reflectivity, $D = Eh^3/12(1 - \mu^2)$ is the cylindrical stiffness of a plate, E is the modulus of elasticity, h is the plate thickness.

The tilt can be calculated for each concrete design too. The greatest possible tilt is at the edge of the plate if it be calculated according to the first model

$$\varphi = \frac{\Delta P}{32D}\left[2r^3 - l_K^2\left(1 + \frac{5+\mu}{1+\mu}\right)r\right].$$

OTHER INFLUENCES

The seismic signal should be cleared of noise in which doesn't contain useful seismic information.

The anelastic deformation of a spring, the effects of vibration on the pendulum and the spring, the humidity, the effect of aspiration and the storm phenomena usually have a smaller impact on the noise generation. However, under certain conditions, these influences can strongly damage a seismic recording.

BSI are known to be sensitive to the magnetic field. Magnetic storms and man-made disturbances of the magnetic field can produce significant noise in seismic recordings. To protect the BSI were successfully used the both method of the passive Permalloy shielding and the method of compensation. An active shielding from magnetic influence provides an improvement of signal-to-noise ratio by almost a factor of 20. However over the last 20 years at installation of seismometers in various areas including in areas with strong technogenic fluctuations of a magnetic field, we have not met the case when influences of fluctuations of a magnetic field couldn't be eliminated by shielding of Permalloy and even simple galvanized iron.

Residual noise of temperature, pressure and magnetic field, both instrumental and transmitted through the ground motion can be minimized by using optimal filtering [5]. It is not so difficult to conduct record-keeping of influence of ground waters level and snow coverage on long and super long periods also.

Another difficulty is related to sensor placement conditions. Seismometer sensitivity to variations in gravity leads to the fact that sensor reacts to the movement of masses close to him (see Fig. 5).

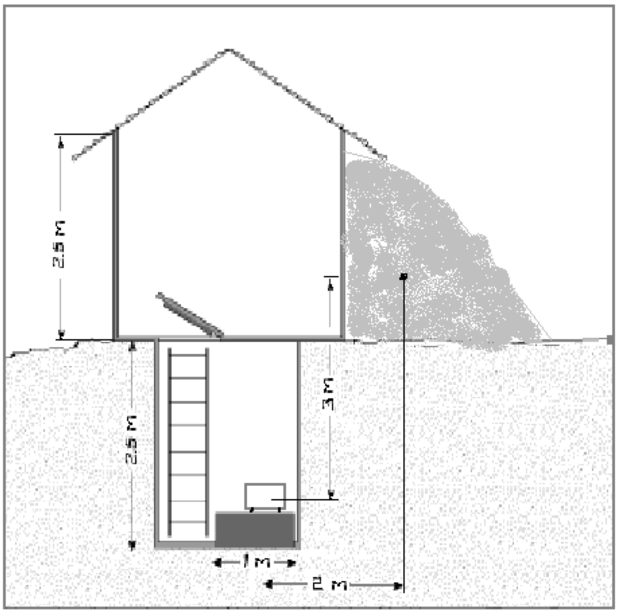


Fig.5. An example of the emergence of mass (snow drift) near the seismometer. The scheme of the station is taken from [6].

At occurrence of the mass *m* on distance *R* from the seismic sensor, its mass will experience acceleration $a = fm / R^2$, where gravitational constant $f = 6{,}67\cdot10^{-11}$ N(m/kg)^2. This acceleration doesn't depend on mass of the sensor, that is, it is the same for all types of devices.

Special BSI may have own specific noise. For example, main noise sources of seismic gyrotiltmeter KST-1 are the radial and axial vibration caused by an unbalance of the gyroscope. Earth rotation essentially affects behavior of this device too. As a result, there are constant moments, which lead the gyrotiltmeter to a new stable equilibrium position. This means appearance of an additional bending of the crossed leaf in rotary flexural system, which in turn will cause extra sensitivity of the device to temperature variations.

CONCLUSIONS AND RECOMMENDATIONS

The main source of environment noise is the temperature. Its influence is multifaceted. Therefore good calculation of a design and good temperature protection are necessary.

The mechanism of transmission of fluctuations of atmospheric pressure to the airproof instrument is known. Thus, we can analytically calculate and design a housing unit in which the pressure disturbance will decrease to the desired value. In such a case, the housing won't be bulky and heavy.

The tilt of the base grows from the center to the edge, and the field of tilt is axisymmetric. Thus the sensors of the horizontal movements should preferably be fixed in the plate center, and farms of their pendulums should be directed along diametrical cross-sections. Seismic sensors are attached to the plate in several points which experiencing different deformation. It is rational to mount the sensor on a separate support, and to fix it to a plate by one ledge which has the minimum area.

Man-made noise is often represented by high-frequency vibrations. The parametric resonance of a vertical pendulum by a resonance of its spring can be the most dangerous result of their influence. It is necessary to choose a spring correctly. In the first place its natural frequencies should be as high as possible and, secondly, they shouldn't coincide with any of the frequencies of a discrete set of frequencies of industrial vibration.

For various designs of seismic sensors and their housing, levels of noise can differ up to 40 dB on the long periods.

A complete set of recommended guidelines for design and testing which may be used by seismometer manufacturers and instrumentation users will be published in the 43 issue of the journal "Computational Seismology".

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