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INSTRUMENT FOR MONITORING SPECTRAL ACCELERATION ON RESPONSE SEISMIC GROUND MOTION

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ABSTRACT
For investigation of influence of various subsoil geological structures on spectral acceleration amplitudes of foundation soil it is necessary to continue in long time monitoring of near seismic events by using of large number of field accelerometers.
The new special apparatus for automatic recording of spectral acceleration response was constructed. Principle of this apparatus is reverse pendulum with piezoelectric converter. This simple construction makes possible production numerous series with small requirements on capital expenditure and installation. The function of developed apparatus prototype was field-tested in station Prague – Květnice. Various seismic signals were recorded and also response amplitude of earthquake with focus near Červený Kostelec (10 October 2005, 10 : 51 : 57.4 ; M = 3.4; R = 156 km; φ = 50.47; λ = 16.07).

KEYWORDS: vibration acceleration, spectral response, seismic recorder, inverted pendulum, transfer function, amplifier, electronic, selective filter, natural frequency, AD converter, damping

1. INTRODUCTION

The value of earthquake hazard to buildings is expressed by various parameters of impacting earthquake ground motion such as peak acceleration (PGA), peak velocity (PGV) spectral acceleration response (SAR) or macroseismic intensity degree (I). According to valid safety guides (IAEA 1991,92,93, NUREG), the earthquake hazard to objects such as nuclear facilities is expressed by functions called Design Spectra (DS). They are smoothened courses of a great number of Spectral Acceleration Response functions SAR (f_S) of a set of elementary vibrators with prescribed resonance frequencies (0.3 Hz $\leq f_S \leq 30$ Hz) having a very small value of damping ($D \approx 0.01$). The shape of a DS depends on magnitude M and on focal distance R, of the expected earthquake. Various response curves were constructed in abroad seismic active regions with moderate- to high seismicity.

Only weak - to moderate seismicity appears in the Bohemian massif. The DS (M, R) and PGA (M, R) functions, derived on the experimental basis of abroad accelerograms, have had to be used in the Czech Republic. Here the near (R < 200km) moderate earthquakes ($M \leq 5$, i.e.. $I_o \leq 7.2$) cause the foremost contribution to the aggregate hazard to localities in this region. (Šimůnek et al., 2005; Buben and Rudajev, 2002).

The reliability of abroad attenuation relations for seismic waves spreading in the Bohemian massif can be verified only on the basis of long-term recording authentic near earthquakes. A special profile consisting of four accelerographs mark MR2000 SYSCOM Swiss was established in the year 2003 (Rudajev and Buben, 2004). Up to the end of 2005, some production blasts, rock-bursts and moderate tectonic earthquakes were recorded. The foci of rockbursts are located in the mine Lubin Glogow (Poland) and some earthquakes originated in the Vienna Basin and Eastern Alps.

Preliminary processing of data indicated that the values PGA and SAR depend not only on M and R but also on the geotectonic structure of rocks where various seismic waves propagate. Continuous recording of input data and their processing have to be carried out for understanding of this complex dependence.

A prototype of developed apparatus is designed especially for completion the hitherto network of macro-seismic observers. Only one of four channels is described in this paper.

2. SPECTRAL ACCELERATION RESPONSE SAR

The **S**pectral **A**cceleration **R**esponse function (SAR) gives maximum amplitude values of vibration of a set of elementary oscillators (e.g. physical pendulums) forced by seismic ground motion. In a graph of this function, the values of natural frequencies f_S (Hz) of pendulums are plotted on the X-axis. On the Y-axis are plotted the values of

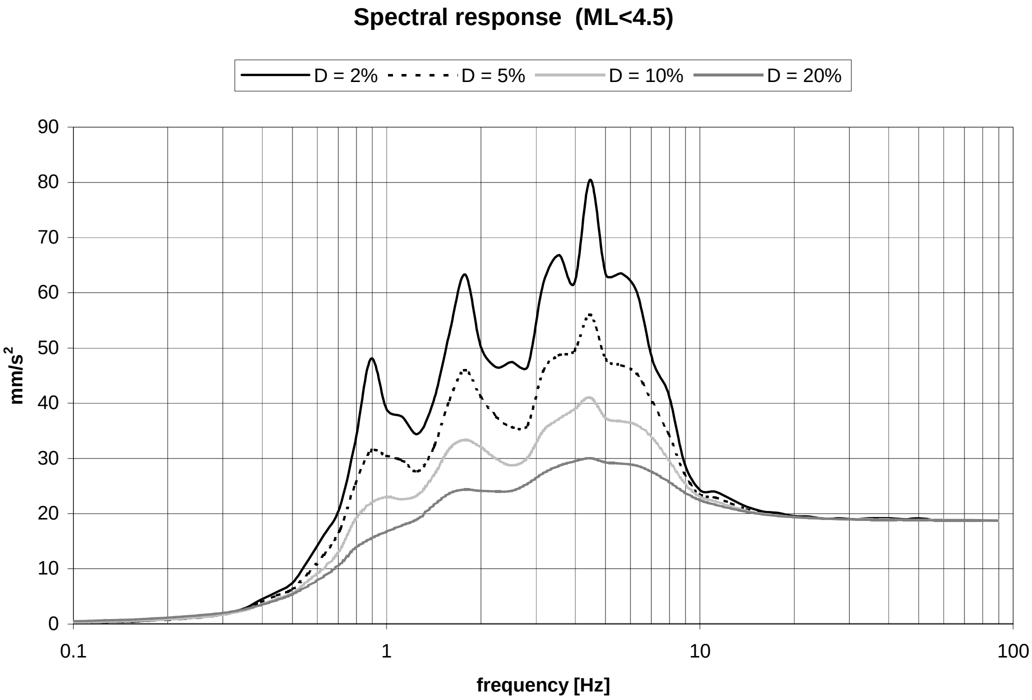

Fig. 1 Acceleration response spectra of Lubin rockbursts in distance R = 160 km.

maximum amplitude A (f_S, D) of forced acceleration of an oscillator with small damping constant D, usually D = 0.01. The values A (f_S, D) obtained from a number of pendulums with various f_S define the course of SAR function for seismic event with magnitude M and distance R. As a rule, the course of response curves is very jagged. Therefore, great number of response curves must be smoothened. Such smoothened curves are called design spectra DS.

The theory proves that the amplitude A (f_S, D) of forced acceleration of oscillators with natural frequency $f_s \gg f_g$ is nearly equal to the value of maximum impacting ground motion acceleration PGA (f_g), where f_g is the frequency of impacting vibrations. In civil engineering, the range of f_s in question is $0.3 < f_S < 30$ Hz. However, the spectral response of building structures (i.e. complex oscillatory systems) reaches its maximum value for frequencies about 4 Hz (Buben and Rudajev, 2004).

Fig. 1 shows smoothened spectral response curves calculated from 10 accelerograms of rockbursts in LUBIN, recorded by accelerographs SON and POT in distances R=100 km and R = 150 km.

Narrow local maxima appear at frequencies 0.9 Hz and 1.8 Hz. A major number of maxima are distributed in the wider frequency band 3.5 Hz to 6 Hz. The positions of maxima are almost not dependent on the value of local magnitude M_L for $2.5 < M_L < 4.5$. The maximum values of SAR are only from 5 mm/s^2 to 11mm/s^2, it means they reach only 1% of the seismic vulnerability of Nuclear Power Plants Temelín and Dukovany.

Due to low-to-moderate seismicity of the region, monitoring period of tenths of years will probably be necessary to obtain authentic accelerograms of local earthquakes with magnitude $M_L > 4$. Specialized instruments "Acceleration Response Monitor” (ARM) were developed, which could minimize economical and technical expenses of this project.

3. APPARATUS DESCRIPTION

The apparatus ARM is composed of four low-damped pendulums with individual natural oscillating frequencies F_s (2 Hz, 4 Hz, 6 Hz and 8 Hz). Such frequencies were chosen with the respect to the shape of the SAR functions mentioned in Rudajev and Buben (2004). The forced oscillations of pendulums are converted to electric signals by means of piezoelectric converter. Subsequent circuit is a low-pass Butterworth, 2nd order filter with cut-off frequency 10 Hz. An external oscilloscope connected to the outlets OSC can be used for recording the analogue wave trains. Next circuits are a two-way rectifier and an analogue storage voltmeter. The rectifier generates absolute amplitudes and the voltmeter stores the peak voltage on a capacitor for a short time interval. The last circuit is a high-to-low impedance converter. The output signal on outlets ADC is led to an analogue-to-digital converter (Fig. 4).

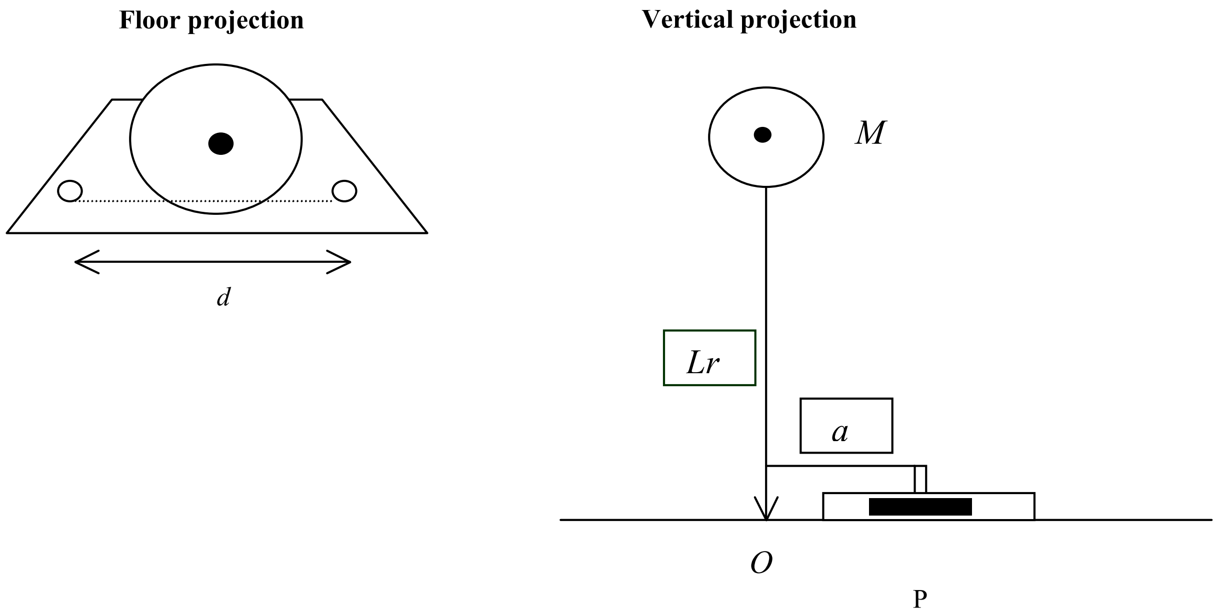

Fig. 2 Reversed pendulum with piezoelectric converter.. *M* - gravity centre, *Lr* - reduced length of pendulum, *O* - rotation axis, *a* - *length of* horizontal arm, P – piezo converter, *d* – distance of support points.

The digitized data is automatically saved (triggered regime) on the disc of PC. The voltage amplitudes are completed by the calendar and time data, which are taken from the PC clock. The above-mentioned circuits will now be described in more detail.

3.1. PENDULUM OSCILLATORY SYSTEM

The mechanic oscillatory system is constructed as a reversed pendulum (centre of gravity above the rotation axis). It is composed of two mutually perpendicular fast joint arms, the upright and the horizontal one. The rotation axis of this pendulum is build-up as two spikes leaning on the base plate of instrument. This pendulum system can tilt from its equilibrium position only by that horizontal component of ground motion acceleration, which is perpendicular to the pendulum rotation axis. The horizontal arm of pendulum leans on the elastic membrane of a piezoelectric converter, which acts as an elastic spring and ensures the equilibrium of pendulum. The sketch of this oscillatory system is given in Fig. 2**.**

The rotation axis *O* is created by two steel needles, which are indented into an acrylic (perspex) plate. The horizontal arm of pendulum leans on nibs of needles forming the support points. The mutual distance *d* of points is 100 mm and the nibs of needles hint upwards. The ball-shaped bob of mass M is fixed on the top of the upright arm. Because of the gravity center of mass *M* lies above the rotation axis, the pendulum is lent on a third point in order to reach its equilibrium.

The supporting spike, fixed to the horizontal arm of pendulum, leans on the center of the circular membrane of the piezoelectric converter. The join *M* - *O* (gravity center – rotation axis) must be declined from vertical plane at a small angle φ. Its value must comply with the demand of sustained link between the supporting pin and the membrane even if the forced oscillations of pendulum reach the maximum expectable amplitude *X*. E.g., the value $\varphi \approx tg\, \varphi = X / Lr = 0.1\text{cm} / 20\text{ cm} = 0.005^{o}$ is sufficient.

The natural frequency F_s of leant reversed pendulum depends on the mass *M* of bob, on the elasticity of the membrane, on the reduced length *Lr* of pendulum and on the distance *a* of the lean point from the rotation axis. The value *a* was set with respect to the possibility of tuning F_s in the desired frequency interval from 2.5 Hz to 10 Hz by convenient values of *Lr*.

At the horizontal acceleration amplitude A_H of seismic ground motion acts on the converter membrane the force P, which is given by relation

$$P = M \cdot A_H k \qquad \text{where } k = Lr/a \,.$$

The stiffness of the membrane is transformed in this ratio *k*, what enables to set natural frequencies Fs to the demanded small values. The advantage of the construction described is that the mass of bob makes itself felt only in action of A_H on the membrane whereas the bob weight is almost fully cushioned by the reaction of bearing support. The apparatus is shown in Fig. 3.

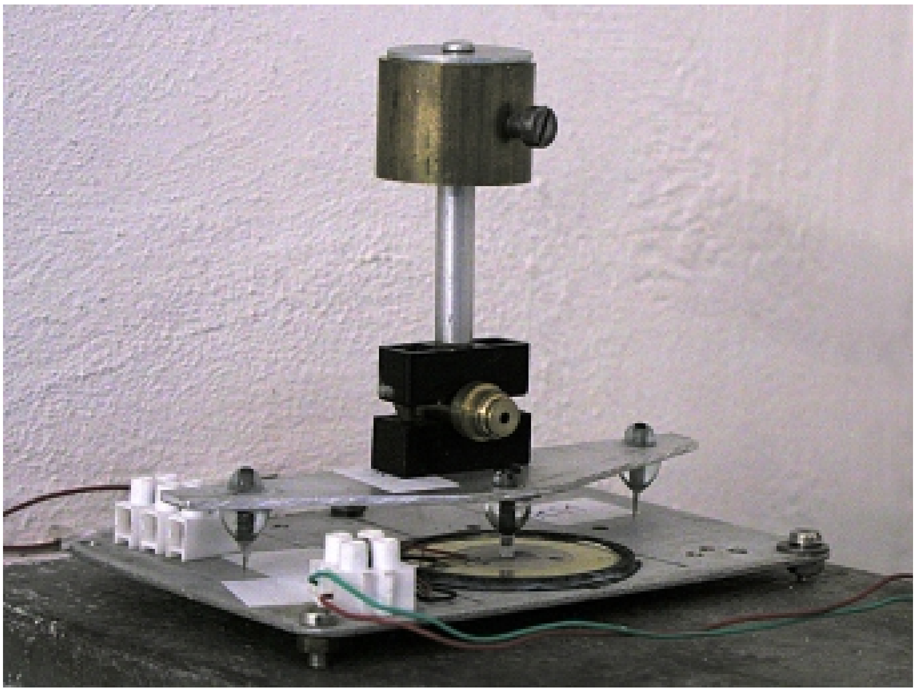

Fig. 3 Apparatus for monitoring spectral acceleration response

3.2. PIEZOELECTRIC CONVERTER

Converter KPS 100 is a component part of loud - speakers or sounders being in off-shelf common use. It is of cylinder shape with diameter 48-50 mm and height 2mm. Its internal capacity is C_i = 65 nF and internal resistance R_i > 20 MΩ. The natural resonance frequency is about 1.2 kHz.

3.3. ELECTRONIC CIRCUITS

Pendulum systems are connected to equal electronic circuits. The wiring diagram of the circuit is shown in Fig. 4.

The whole electronic block consists from six equal integrated operation amplifiers U2A, U2B, U3A, U3B, U4A and U4B.

The circuit U2A operates as charge amplifier. For $R_1 \gg 1/(2\pi f)$, the output voltage E_2 of this circuit is

$$E_2 = E_1 \cdot C_i / C_2$$

where

E_1 is the voltage on piezoelectric converter KPS 100,
C_i = 56 nF is the capacity of the converter,
C_4 = 47 nF is the capacity of the feed – back capacitor.

The transfer function B_2 of charge amplifier is given by the relation:

$$B_2 = E_2 / E_4 = C_i / C_2 = 1.19 .$$

Low frequency limit of the charge amplifier depends on the time constant τ, ie., the product of feedback resistance 10M and the internal capacity C_i of piezoconverter (τ = 0.56 s). Transfer of this amplifier is constant for frequencies greater than 2 Hz.

The U2B operates as low-pass filter of 2nd order, Butterworth, (Hájek and Sedláček, 2002). The wave train on its outlets OSC can be recorded by a digital oscilloscope.

Transfer function B_3 is adjusted by the values $R_2 = R_3 = R$ = 0.130 MΩ and $C_5 = C_6 = C$ = 0.100 µF (see Fig. 4). It is flat for frequencies up to the cut of frequency $f_o = 1/(2\pi RC) = 12.2$ Hz . The voltage gain in the segment of constant transfer B_3 is adjusted by resistors R4 and R5 according to relation (Láníček, 1998):

$$B_3 = 1 + R_4 / R_5 = 1 + (0.09\ \mathrm{M\Omega} / 0.15\ \mathrm{M\Omega}) = 1.6$$

The U3A and U3B operate as full wave rectifier. The U4A is a peak-value-storage voltmeter. The reached peak voltage on the storing capacitor decreases slowly with time. The appropriate rate of decrease is adjusted by means of an external resistor, connected parallel to the storage capacitor via outlets STOP. The U4B operates as high-to-low impedance transformer. Its input is connected to the storage capacitor and the output of U4B can be connected to the analogue-to-digital converter via outlets ADC. The output voltage on ADC can be set to zero by short cutting the storage capacitor - outlet STOP.

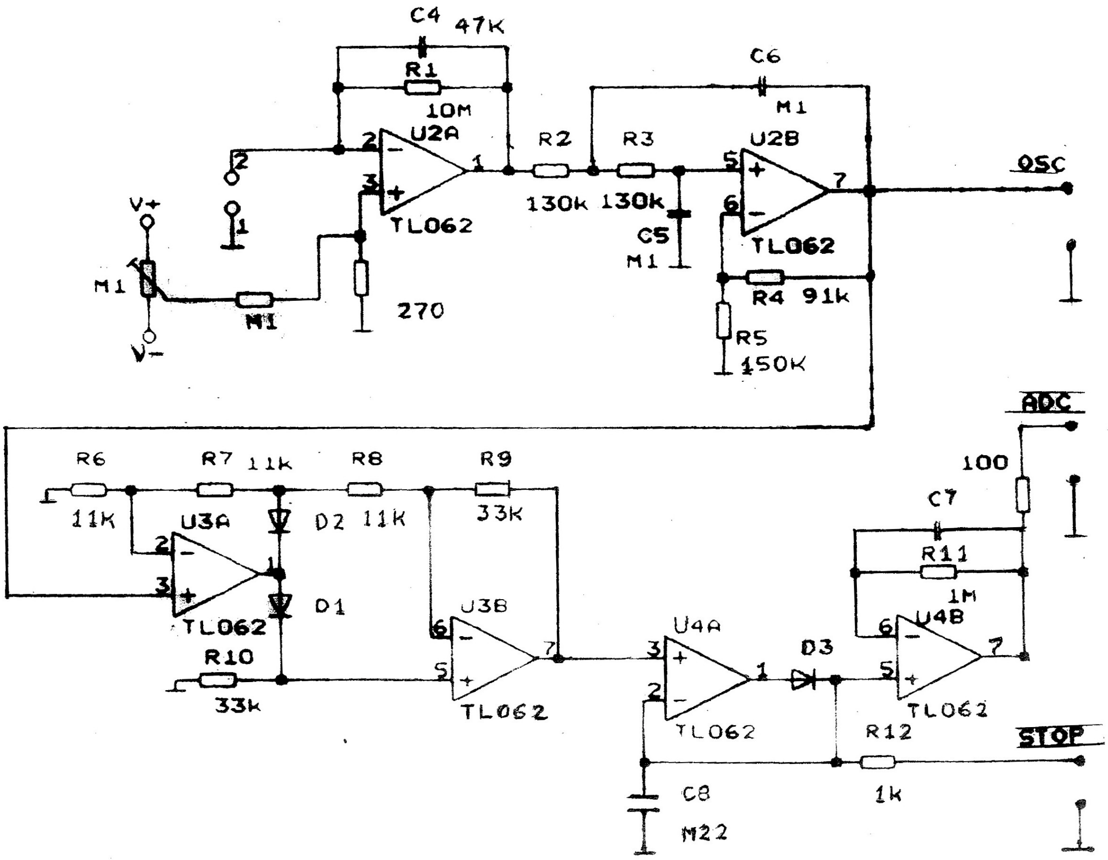

Fig. 4 Wiring diagram of electronics.

4. A-D CONVERTER AND PC RECORDER.

The integrating type converter Mark AD232, manufactured by the firm Janas Card, Praha, was used. Its unusually low sampling frequency - only 10 samples/s - is quite passable due to used analogue data pre-processing. This converter can be connected to PC via serial port RS 232, from which it is powered, too. Technical data of AD232 are as follows:

Discrimination: ± 15 bit.
Range: 0.5 Volt or ± 5.0 Volt.
Number of channels: n = 4.
Sampling frequency: 16 / n.
Input resistance: 1.1 MΩ.
Noise: 15 μV.

The AD232 can create the average value STA (Short-Time-Average) of selectable number of samples. Due to this averaging, the rejection of disturbing signals increases. The practically attainable discrimination 2μV can be obtained at averaging at least 19 samples.

A low-cost PC (e.g. Pentium II, DOS operation system) approved itself as quite satisfying recording device. Especially, the use of a notebook (e.g. DELL XPi) makes possible the low wattage and autonomy of power supply. Moreover, an external accumulator with suitable capacity can substitute the original battery and serve as autonomous power supply 12V, 1A.

5. TIME BASIS DCF 77 TIME CODE RECEIVER

The calendar and time date is taken from the PC system clock. They are synchronized with atomic clock PTB (Braunschweig) by means of time signals given by radio station DCF 77. Useful hardware, mark RPC-B-UP-200-DOS (Radio Precision Clock for MS DOS), is supported by the firm Procon ltd. Česká Lípa, and distributed by firm OMNIPRES, Prague. It consists of a DCF 77 receiver and corresponding software RPC-B-DOS, which adjusts the internal PC time according to time signal received. This device operates under the DOS and can be connected to the port COM 2. The received time information is logically checked. The updating is carried out merely when two consecutive calendar data are equal or time data differ only in one minute. The received time information is always indicated on the monitor of PC.

6. SOFTWARE

The original software, written in Turbo Pascal, performs triggered record of up-to four channels. Data are stored on PC disc only if the voltage on ADC

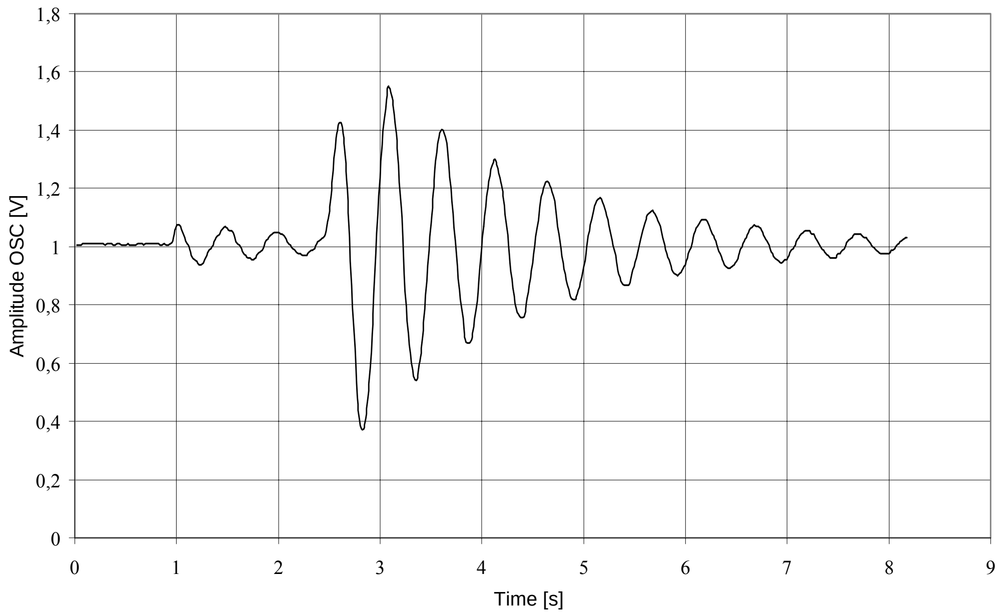

Fig. 5 Natural frequency

outputs exceeds a threshold value and it is greater than foregoing voltage. The threshold voltage is prescribed with respect to the quasi-stationary seismic noise and to the frequency of random disturbing events. The long-term-averaged value (LTA) is calculated from a selectable number of samples (usually about 100).

The voltage of first amplitudes on all of four channels, exceeding the threshold value, are written in new lines of the output file together with the current year, month, day, hour and minute. The values are written only if their amplitudes are greater than the immediately foregoing ones (Fig. 6).

The output file name is created automatically when the recording program is started. It indicates the month, day, hour and minute of program starting. The template of filename is mm dd hh nn . *. The double-figure numbers do mean as follows : mm-month in year, dd-day in month, hh-hour in day, nn-minute in hour and the extension is used for identification the station, software etc.

Pressing the space bar initiates the termination of program. Thereafter the program automatically writes into the last line the calendar and time of termination. Before definite saving of output file, the operator is questioned on remarks (e.g. observed events and / or time correction, taken from independent clock).

7. CALIBRATION

The calibration procedure consists of the steps as follows:

7.1. Determination the natural frequency F_s of the pendulum system and its damping constant D.

7.2. Determination the relation of output voltage U (outlet ADC) to the amplitude A of ground motion acceleration vibration.

7.3. Determination the relation between the output voltage U and the corresponding numeric value C written in the output file.

7.1. NATURAL FREQUENCY AND DAMPING CONSTANT OF PENDULUM.

The natural frequency F_s was determined from digital records of free vibration on a standard digital oscilloscope, connected to the outlet OSC. The example of recorded oscillation of described system is shown in Fig. 5. Here, the values of amplitude are plotted on the Y-axis and the time is plotted on the X-axis.

The damping constant D can be calculated from digitized amplitudes of natural oscillation using the well-known relation

$$D = 0.733 \log_{10} (A_i / A_{i+1})$$

where A_1, A_2 ….., are peak-to-peak amplitudes, succeeding one by one in time intervals $T/2 = 1/(2F_s)$.

In the case of pure viscous damping, the decay of envelope curve Y(t) of amplitudes with time t agrees with the exponential relation

$$Y = \exp(-D \cdot 2\pi f_s)$$

The values D are small enough and they correspond to values, prescribed for the IAEA design spectra. Therefore no additional damping equipment in pendulum systems is necessary. Exponential course of envelope curves indicates the viscous character of residual damping despite of the not quite unique contact between the supporting pin and the converter membrane. The value of dry friction is negligible.

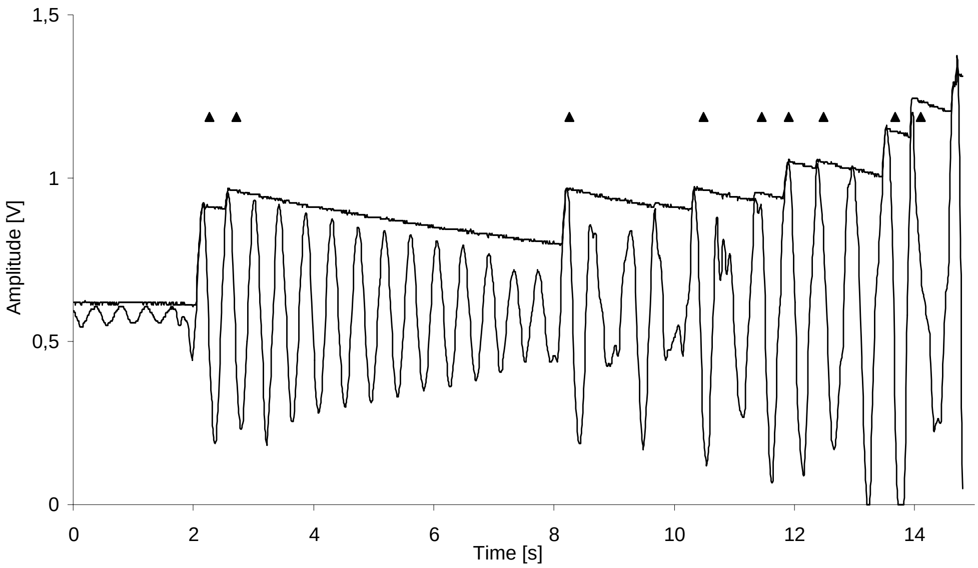

Fig. 6 Signal on outputs OSC and ADC.

7.2. TRANSFER OF PICKUP AND ELECTRONIC BLOCK

The transfer B is defined by relation

$$B = U/P, [Vs^2 /(kgm)]$$

where U is the voltage on outlets ADC of electronics block and $P = M \cdot A$ is the force acting on the gravitational center of bob M [kg]. A is the horizontal component of ground motion acceleration [m/s^2].

The transfer was measured using an additional small bob M, acting on the gravity center of pendulum in the horizontal direction. The bob M = 0.01 kg was hinged on a silon fibre, which was fed over a capstan and fixed to the pendulum in point of its gravity center. The small step of force p, acting on the pendulum when the fibre is abruptly disconnected, is

$$p = m \cdot g = 0.01 \text{ kg} \cdot 10 \text{ ms}^{-2} = 0.1 \text{ kgms}^{-2}.$$

The corresponding step in output voltage U = 0.16 V on outlets ADC has been determined experimentally. The so determined transfer is

$$B = 0.16/0.1 = 1.6 \text{ Vs}^2/(\text{kgm}) .$$

The amplitude characteristics of the active pickup (pendulum and electronics) is

$$U = B \cdot P = B \cdot M \cdot A = 0.64 \cdot 1.6 \cdot A = 1.02 \cdot A, \quad [V, kg, m \cdot s^{-2}]$$

where the mass of pendulum bob is M = 0.64 kg.

The amplitude characteristic U_{dyn} (A) for quasi-stationary sinusoidal vibration $A = A_o \sin(\omega t)$ can be obtained by multiplying U by $ß = 1/(2 \cdot D)$ of resonance surpass of forced vibration.
For the experimental sample of pickup with F_s = 2 Hz the damping constant is: D = 0.05 and β = 10.

The dynamic amplitude U_{dyn} characteristic is

$$U_{dyn} = U \cdot ß = 10 \cdot A \ , [V, \ ms^{-2}].$$

The peak acceleration amplitude A is given by relation:

$$A [mm \cdot s^{-2}] = 0.1 \ U_{dyn} \quad [mV].$$

7.3. TRANSFER OF THE AD CONVERTER.

The used range of AD converter is set on ± 5.0V and the output data are multiplied by the coefficient 1000. In this configuration, the voltage U = 1V on the ADC input is written in the output file as C = 1000. It follows that the written value of output voltage U_{dyn} [mV] = C.

An example of signal on outputs for OSC (vibration) and ADC (envelope) is shown in Fig. 6. In time, denoted by triangles, the values of envelope exceed the foregoing value. These times and corresponding values are stored in the output file.

8. CONCLUSION

An experimental specimen of one-channel apparatus with f_S = 3.5 Hz is in experimental operation in the site (φ = 50.1179^O N, λ =14.4640^{O}E) since 30.08.2005. Earthquake near Hronov town
(ML = 3.4, φ = 50.47^0 N, λ = 16.07^0 E, h = 6 km) appeared 25. 10. 2005, at local time 12 h 51 min. The

radial component of horizontal ground motion was written as C = 28, it means U_{dyn} = 28 mV. This value corresponds peak acceleration amplitude A = 2.8 $mm.s^{-2}$. The seismic station IRSM - Prague recorded the values A_{NS} = 0.59 $mm.s^{-2}$ and A_{EW} = 0.46 $mm.s^{-2}$ in epicenter distance 120 km.

The first experimental series of four instruments will now be used in some sites of Prague town, where a monitoring system of supposed micro-zoning project could be prepared. The site specified attenuation formulae (Rudajev and Buben, 2005) can be verified and improved by establishing a great number of described instruments.

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