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THE ABDUS SALAM INTERNATIONAL CENTRE FOR THEORETICAL PHYSICS

CUBAN SEISMIC NETWORK SHORT PERIOD SEISMOMETER CALIBRATION

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Abstract

The dynamical calibration of short period sensors, largely used in Cuban seismic network is presented and differences between this method and other results obtained according to the theoretical methods are established. The new and practical module and phase response curves are presented in both, graphical and file configurations.

To obtain this result, a calibration table is used, connected, through a 24 bits digitizer, to a PC using LINUX operating system. The data obtained are processed with the software VIBROCALC, under MATLAB in WINDOWS platform.

Finally, we analyze different types of passive damping using resistances connected to the seismometer main coil and their effect in the sensibility of the sensor as well as the limitations inherent to this methodology. Also the use of feedback circuits for active damping is shown including comparison between this and those with resistances.

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Introduction

The National Center for Seismological Research (CENAIS) operates, through the National Seismic Survey (SSN), a network of seismic stations distributed around the country and organized in different networks which cover, in dynamic range and spectral composition, almost all earthquakes at local and regional levels, including those with big energy anywhere around the world.

The main network used for local seismic activity monitoring is short period telemetrically which has a Russian made sensor name CM-3.

This kind of seismometer is defined by a low electromagnetic constant as well as low sensibility because of very small resistance values in sensor coils, one used for the velocity signal extraction and the other to achieve the maximum possible damping.

Due to these characteristics, and from sensibility point of view, it was necessary to place, an amplifier to enlarge the signal level to more reliable limits, between the sensor and the digitizer, in their first version, we designed feedback circuits which use operational amplifier with resistances, they allow to reach amplifications on the 500 units order, but they are situated in the same print circuit where microprocessors, memories and A/D converters are switching, and began to arise problems with induced noise and off set variations. A second design, which used external amplifiers reduced considerably this problem although it is necessary to clarify that, when we amplified notably the useful signals, the same thing with noise is done, and this situation can make influence in a decrease of the seismometric channel dynamic rank.

Nevertheless, the way to obtain frequency response is more complicated, because there are some limits in maximum damping obtained by short circuit of one seismometer coil.

Calibration.

The essence of the seismometric channel is the calculation of the instrument transfer function used for ground movement record; it is because his influence on the signal which is not linear and follows a second order equation. It means that seismometer has a complex response in a frequency domain.

The calibration methods can be divided, in general form, in those in which the frequency response is calculated using the individual constant values of each element in the system and the others, in which the sensor is considered like a "black box", in which an input signal simulating the ground movement, produce the output signal which contain the information about the frequency response, in terms of phase and amplitude.

This is especially true in the modern seismometry, where the sensors, besides the mechanics inherent in their construction, have an electronic feedback circuits with the specific function to enlarge the corner frequency in the low frequencies and to generate, in other cases, dynamic over damp.

Keeping in mind, the own characteristics of this sensor and the non-existence of calibration coil for its connection to digitizer, and its calibration by signal injection from analysis software, we used the theoretical equation evaluation which represent the mathematical approach to seismometer behavior in order to obtain the normalized curve and the subsequent reintegration in the software [Cutie M., Diez E., Serrano M.; 2000].

The evaluation of the equation,

$$VS(s) = \frac{E(s)_{out}}{\dot{X}(s)} = \frac{G_d s^2}{s^2 + 2\zeta\Omega s + \Omega^2} \qquad \frac{V}{m/s}$$

where:

Gd: Electromagnetic transduction constant.

VS: Sensibility.

$E(s)_{out}$: Seismometer coil terminals voltage.

X(s) : Ground velocity.

Resonance frequency fo on the form: $f_0 = \frac{\Omega}{2\pi}$

ζ : Damping ratio.

For this sensor produces, as solution, a table of values and frequency response diagram shown in figure 1 as well as in table 1.

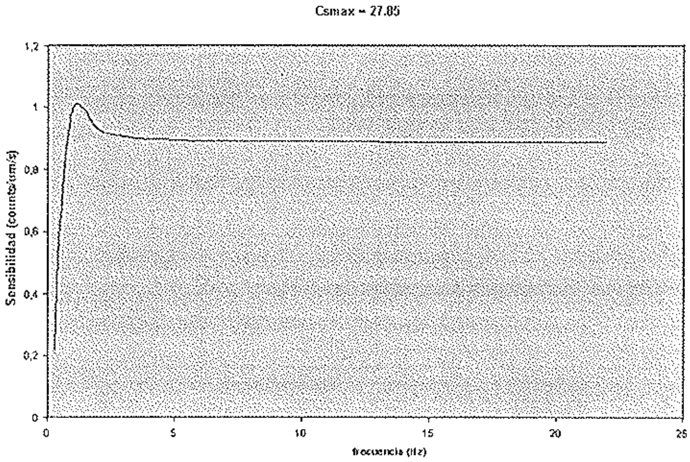

Figure 1: Short period response curve, theoretical method.

Freq [Hz]	*Cs (f) [Counts/um/s]*
.3	.2235502
.5	.6298676
1	1
2	.9272826
3	.9064674
4	.8988667
5	.895302
6	.8933541
7	.8921757
8	.8914095
9	.8908834
10	.8905068
11	.8902281
15	.8896139
20	.8893009

Table 1: Theoretical response.

The error induced to this mathematical approach and the variations of the sensor mechanical components caused by time and climatic conditions cause that the curve obtained does not constitute a good reference in comparison with the real instrument frequency response.

This paper shows a dynamic calibration methodology which, using a shake table, simulates the ground displacement, exciting the sensor with Gaussian white noise, tampered and filtered according to seismic bandwidth, this method allows one to obtain, of a single time, the phase and amplitude module frequency response of the instrument under test, keeping in mind all seismometer electro mechanic characteristics because of time, weather conditions and structural modification of sensor made materials.

Also, the frequency response for different damping values are shown using coil short circuit, in addition with some resistances connected in parallel with main coil, finally the most useful and reliable method with feedback circuits is described with his all benefits.

Method

One of the second type of calibration methods explained before is dynamical, which use a shake table and consider short period sensor like a box without any details about his specific characteristics and looking at him as an element which receive an excitement signal and generate response in terms of amplitude and phase not uniforms in the interest frequency bandwidth.

In this case, we did simplest evaluation of CM-3 seismometer, without intermediate electronic circuits, with the following data supplied by the manufacturer:

Sst (main coil sensibility)= 17 [V/m/s]
Ssa (damping coil sensibility)= 17 [V/m/s]
Lo (equivalent pendulum longitude)= .084 [m]
Kf= .0085 [Kgm^2]
Ra (mail coil resistance)= 59 [ohms]
Damping = 0.25
To = free period=1second.

According to provided data, we observed some peculiarities, as follows:

1. Little sensibility and low electromagnetic transduction constant; because of small coil resistance and the characteristics of the material of construction of the magnet.

2. Insufficient damping (0,3 of the maximum 0,7) as shown in figure 1, this causes a resonance peak around the free oscillation frequency; keeping in mind that this result is obtained by short-circuit the damping coil (maximum possible), the result is unuseful, we analyzed some solutions with passive and active damping.

Keeping in mind the previous characteristics, we carried out the calibration by the following schematic diagram:

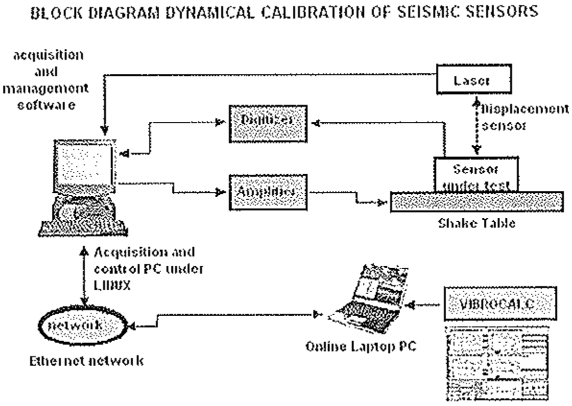

Figure 2: Shake table calibration block diagram.

To carry out the primary test, the calibration coil was short-circuited and the sensor was placed on vibrator surface (see appendix 1), which was excited, through an amplifier, with a white noise signal, filtered and limited to the interest band for the analysis of the instrumental response, [Di Bartolomeo P., Ponton F., Urban S., Zuliani D.;2005] (appendix 3).

The displacement was controlled by laser position sensor. Both resultant signals, one from seismometer output and the other from laser, previously digitized and quantified, where the elaboration program inputs for the instrumental response determination, just they are shown in figures 3 and 4.

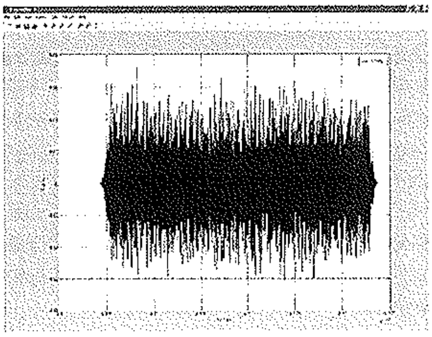

Figure 3: Displacement signal (laser).

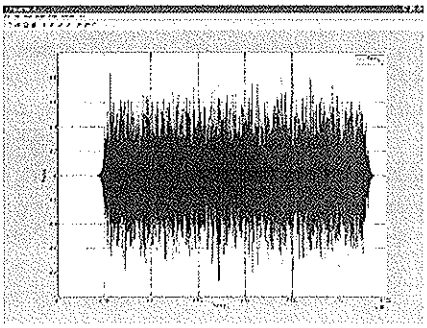

Figure 4: Seismometer output signal.

The program VIBROCALC (see appendix 2), carries out the calculation of the spectral response of two signals called A and B, in the following form

H(f)= Channel B(f) / Channel A(f)

With six different mathematical methods and wrote on MATLAB 6.5 (WINDOWS platform) shows, at the same time, the obtained result and gave, with enough flexibility, the change of parameters and frequency limits for calculation.

Using as input, the signals shown previously in figures 3 and 4, and choosing the method TFE; Transfer Function Estimate (appendix 8), the seismometer response curve in frequency band desired is obtained, in module and phase (appendices 4 and 5).

After analyzing the curves and their values to specific frequencies, some notable differences between the theoretical method and the dynamic one are shown.

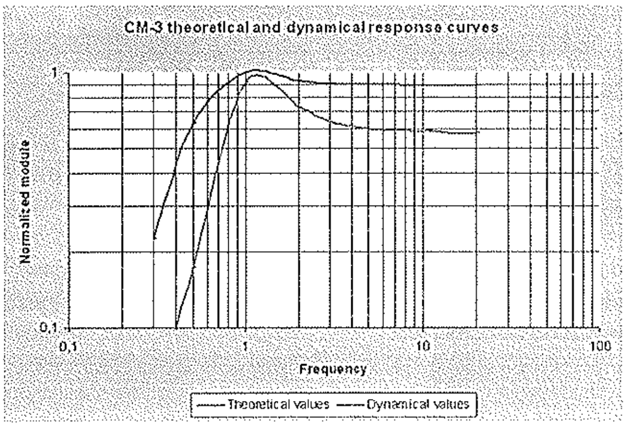

Figure 5: Seismometer response comparison

Freq. [Hz]	*Theoretical Method*	*Dynamic Method*
.3	.2235	.0462
.5	.6298	.1722
1	1	.9167
2	.9272	.7369
3	.9064	.6424
4	.8988	.6147
5	.8953	.6013
6	.8933	.5955
7	.8921	.5917
8	.8914	.5897
9	.8908	.5883
10	.8905	.5880
11	.8902	.5886
15	.8896	.5760
20	.8893	.5808

Table 2: Theoretical response comparison

According to figure 5 and table 2, we observed the following differences:

1. The maximum value of the module was obtained in the frequency of 1.10 Hz (obviously, this value is nearby to adjusted period of seismometer free oscillations and the differences should be due to errors in the adjustment).
2. The value of the coefficient grows, since 27.85 in the theoretical method, until 29.20 in the practical.
3. Below 1 Hz, the frequency response of the instrument falls abruptly, with a slope bigger than previously calculated.
4. The difference among the peak value, 29.20 v/m/s and the those in the "flat" part of the curve, between 16 and 17 v/m/s, result in a difference around the 40%, in comparison with the 11% calculated by the theoretical method.

Another characteristic, which is appreciated, is the resonance peak in the neighboring pendulum free oscillation frequency, due to low damping obtained below 0.3, owed of low value in the used coil resistance.

For this kind of sensor, the maximum possible damping could be obtained by coil terminals short circuit, but keeping in mind that it is not enough, we analyzed the enlarging of this value connecting different resistance values in parallel to the signal coil, this kind of damping, called passive. The disadvantage of this method is that it reduce, at the same time in which increase the impedance value, the amplitude of the useful signal from this coil for its subsequent amplification and digital conversion. Of course, the limit that imposes this commitment causes that this procedure itself can not arrive to 0.7 damping coefficient.

In figures 6 and 7, the seismometer response curves for the damping resistance values: 2,2 K ohm, 1 K ohm, 500 Ohm, 200 Ohm and in open circuit are observed, there is confirmed an effective decrease of the resonance peak without arriving, in any case, to eliminated this, also from value of 500 ohms and less, in line with it, is appreciated too a decrease of module values in the flat part of the curve which made the instrument less sensitive.

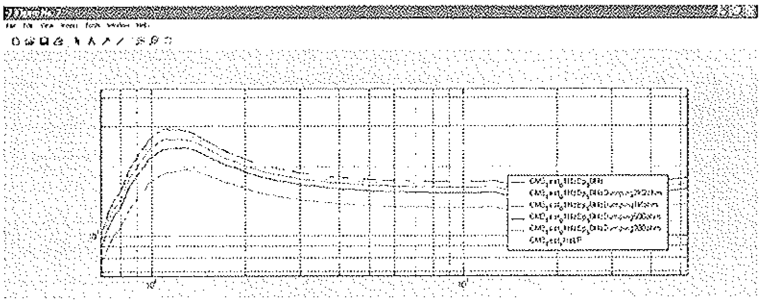

Figure 6: Different frequency response curves obtained thought variation of the resistances connected in parallel to the main coil.

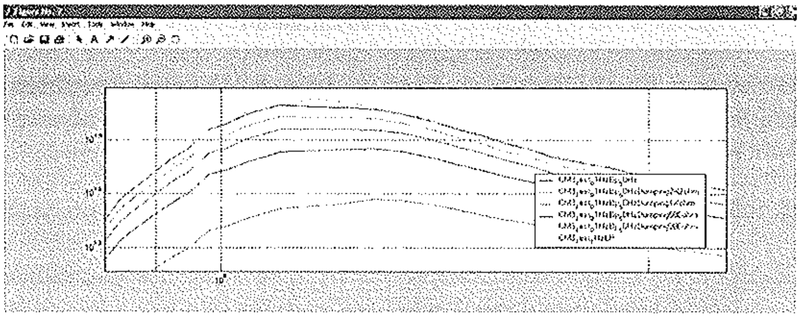

Figure 7: Curves expanded showing the resonance zone of pendulum response...

Logically, the ideal solution decreases the value of this resistance to zero or nearby values and can be obtained by made coil terminal short-circuit, but this case, unuseful, eliminate the formation of the potential difference through this coil equivalent to the ground velocity; for which this method is ineffective. Also, the connection of negative impedances which can generate damping coefficients around 0.7 is not possible by the use of passive resistances.

The proposal to resolve this problem, involves the use of active feedback circuits which permit to reach damping on the order of 0.7 and more [Ulmann B.; 2005], without any negative influence in the signal amplitude at the main coil output neither in the sensibility of the instrument.

According to electric diagram shown in appendix 6 [Lennartz] and carrying out the electrical connections in the right form, for this type of sensor, a response curve remain as average, the own seismometer sensibility in the flat part of curve (around 17), but eliminates the undesirable resonance peak in the frequency of free oscillations (see appendix 7).

Finally, in figure 8 the comparison among the seismometer response curve is shown with active damping and the same obtained with main coil open circuit, both by shake table. It is clear that the method remained efficient and eliminated the resonance peak caused by the under damping system and made a good approach to standard and common use seismometer response curve for short period seismometers.

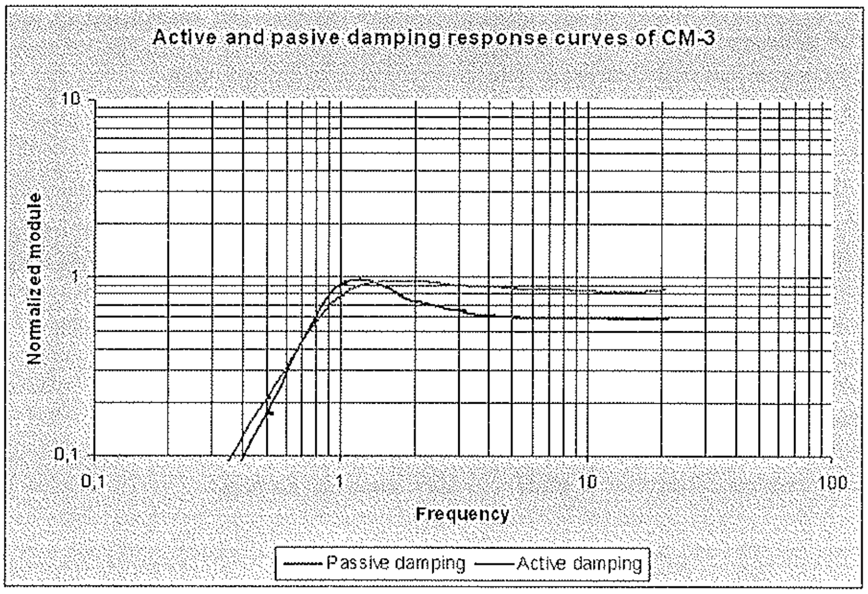

Figure 8: Frequency response comparison of CM-3 short period sensor with open main coil and with active feedback damping circuits.

Conclusions

Enough differences where observed between practical and theoretical methods for CM-3 seismometer calibration, which justify and validate the use of this method for the adjustment of seismic sensors, summarized in:

1. Different values of calibration constant values.
2. More abrupt cut-off in low frequencies of the seismometer response.
3. Relations on the order of the 40% between the maximum value, near the resonance peak and the flat part of the response curve, considered undesirable to the effects of its use in seismic analysis software due to the induced error.
4. Impossibility to achieve passive damping more than 0.3 using damping coil and limited results using resistances connected in parallel to signal coil.
5. Use of active circuits for damping which allows system to approach value of 0.7.

Recommendations

It is recommended, first of all, to update the instrumental response curves, in their tabulate form, in the seismic software programs of the telemetric network, for all stations that use the same type of sensor.

In order to obtain a more standardized response, it is recommended to move to active damping methods using electronic feedback circuits which can guarantee to reach a normalized damping of 0,7.

Also, it is recommended to repeat, yearly, the calibration using this method to check any possible changes in response curve in terms of amplitude and phase due to variations in seismometer mechanical and electronic parts.

Acknowledgments

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References

[Cutie M., Diez E., Serrano M.; 2000], Metodología para la calibración de los canales sismométricos de las Redes Telemétricas de corto período en el Sistema del Servicio Sismológico Nacional.

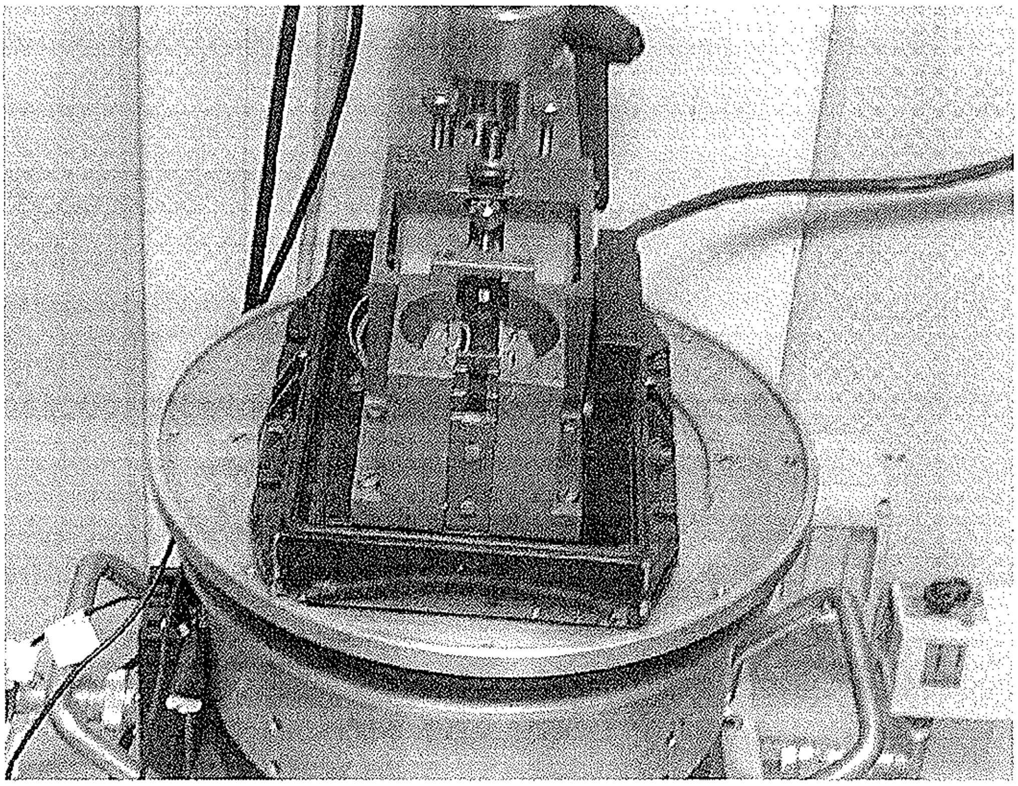
[Di Bartolomeo P., Ponton F., Urban S., Zuliani D.;2005], Relazione tecnica relative al metodo diretto di calibrazione di sensori sismometrici tramite tavola vibrante, OGS internal report.

[Ulmann B. ;2005], Overdamping geophones using negative impedances.

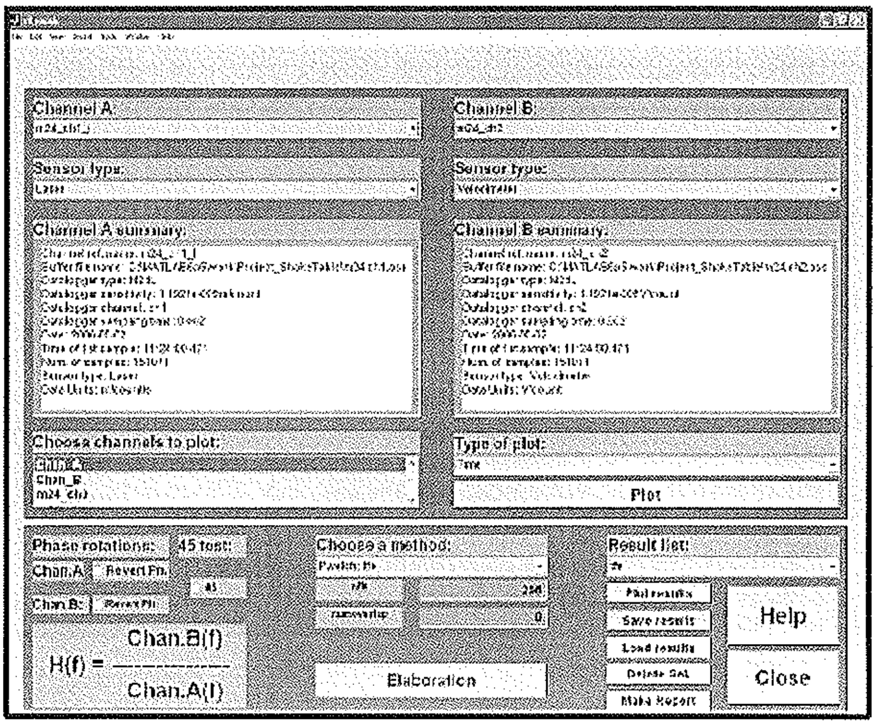
[Lennartz], Lennartz electronics GmbH, LE-xD Geophone Family.

APPENDICES

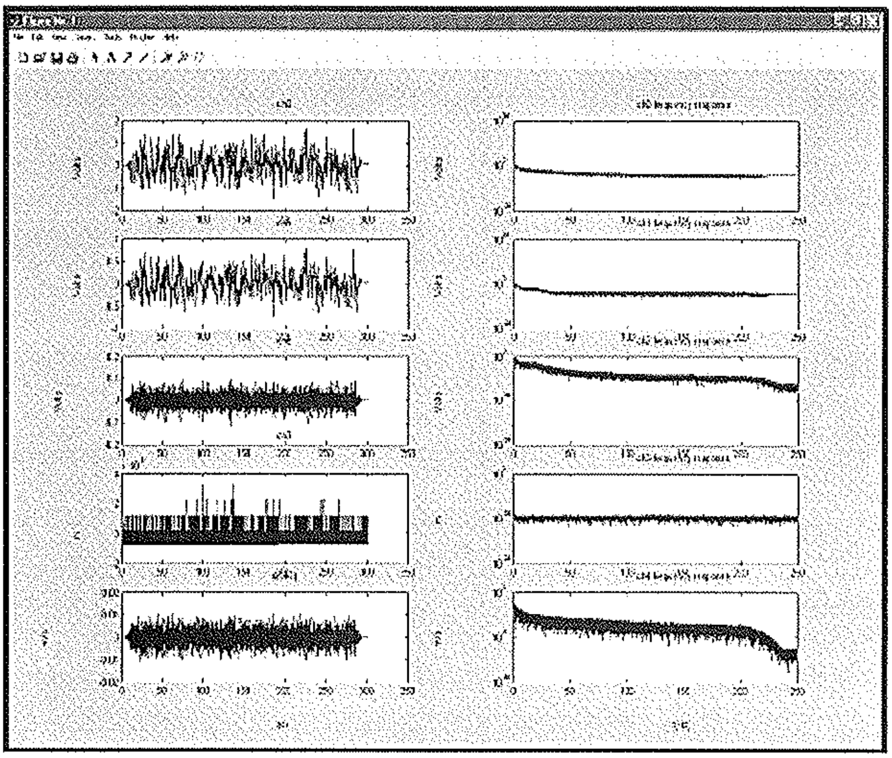
Appendix 1. CM-3 seismometer under test.



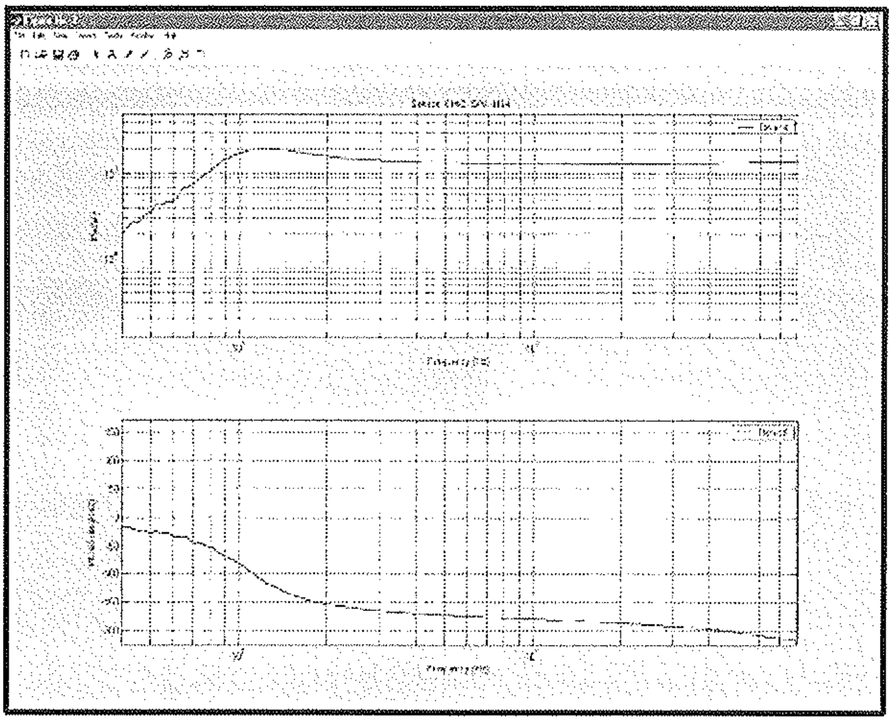
Appendix 2. Main VIBROCAL windows.



<u>Appendix 3.</u> Input and control signals.



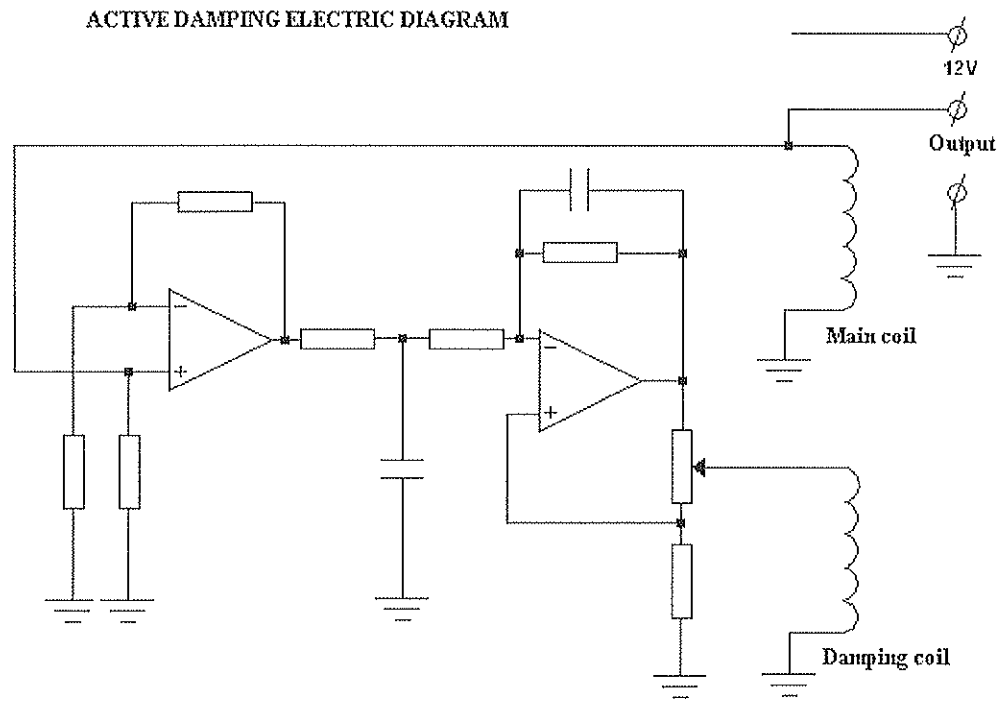
<u>Appendix 4.</u> CM-3 seismometer response curve (module and phase).



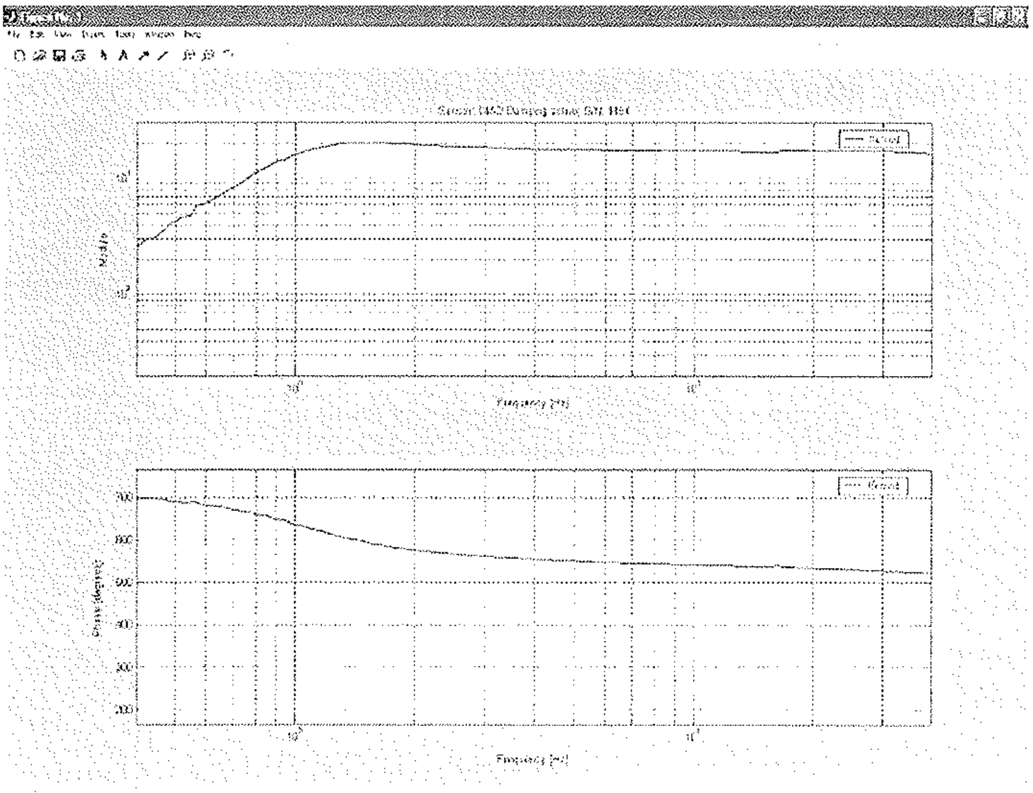
Appendix 5. CM-3 seismometer response curve (module and phase), table of values.

Frequency [Hz]	Module [V/(m/s)]	Phase [°]
0.10	0.47	-76.57
0.20	0.74	-23.58
0.30	1.35	10.39
0.40	2.16	-375.99
0.50	5.03	-379.47
0.60	6.86	-28.46
0.70	10.68	-39.92
0.80	15.79	-47.16
0.90	22.27	-63.71
1.00	26.77	-80.24
2.00	21.52	-157.63
3.00	18.76	-167.92
4.00	17.95	-172.34
5.00	17.56	-174.87
6.00	17.39	-176.65
7.00	17.28	-178.03
8.00	17.22	-179.17
9.00	17.18	-180.18
10.00	17.17	-181.06
15.00	16.82	-184.66
20.00	16.96	-187.29
25.00	17.03	-189.85
30.00	17.12	-192.29
35.00	17.22	-194.70
40.00	17.36	-197.02
45.00	17.54	-199.42
50.00	17.70	-129.71
55.00	17.90	156.01
60.00	18.17	153.39
65.00	18.24	150.22
70.00	18.05	148.67
75.00	18.22	147.36
80.00	18.29	145.35
85.00	18.37	142.19
90.00	18.64	141.35
95.00	18.24	137.92

<u>Appendix 6.</u> Electric diagram of active damping circuit.



<u>Appendix 7.</u> CM-3 response curve (module and phase) with feedback damping circuit.



Appendix 8. Mathematical method used for calculation (extracted from MATLAB 6.5 help).

TFE

Estimate the transfer function from input and output

Syntax:

```
Txy = tfe(x,y)
Txy = tfe(x,y,nfft)
[Txy,f] = tfe(x,y,nfft,fs)
Txy = tfe(x,y,nfft,fs,window)
Txy = tfe(x,y,nfft,fs,window,numoverlap)
Txy = tfe(x,y,...,'dflag')
tfe(x,y)
```

Description:

Txy = tfe(x,y) finds a transfer function estimate Txy given input signal vector x and output signal vector y. The transfer function is the quotient of the cross spectrum of x and y and the power spectrum of x.

$$T_{xy}(f) = \frac{P_{xy}(f)}{P_{xx}(f)}$$

The relationship between the input x and output y is modeled by the linear, time-invariant transfer function Txy. Vectors x and y must be the same length. Txy = tfe(x,y) uses the following default values:

- nfft = min(256,(length(x))
- fs = 2
- window is a periodic Hann (Hanning) window of length nfft
- numoverlap = 0

nfft specifies the FFT length that tfe uses. This value determines the frequencies at which the power spectrum is estimated.

fs is a scalar that specifies the sampling frequency.

window specifies a windowing function and the number of samples tfe uses in its sectioning of the x and y vectors.

numoverlap is the number of samples by which the sections overlap. Any arguments that are omitted from the end of the parameter list use the default values shown above. If x is real, tfe estimates the transfer function at positive frequencies only; in this case, the output Txy is a column vector of length nfft/2+1 for nfft even and (nfft+1)/2 for nfft odd.

If x or y is complex, tfe estimates the transfer function for both positive and negative frequencies and Txy has length nfft. Txy = tfe(x,y,nfft) uses the specified FFT length nfft in estimating the transfer function.

[Txy,f] = tfe(x,y,nfft,fs) returns a vector f of frequencies at which tfe estimates the transfer function. fs is the sampling frequency. f is the same size as Txy, so plot(f,Txy) plots the transfer function estimate versus properly scaled frequency. fs has no effect on the output Txy; it is a frequency scaling multiplier.

Txy = tfe(x,y,nfft,fs,window) specifies a windowing function and the number of samples per section of the x vector. If you supply a scalar for window, Txy uses a Hann window of that length. The length of the window must be less than or equal to nfft; tfe zero pads the sections if the length of the window exceeds nfft.

Txy = tfe(x,y,nfft,fs,window,numoverlap) overlaps the sections of x by numoverlap samples.

You can use the empty matrix [ ] to specify the default value for any input argument except x or y.

For example, Txy = tfe(x,y,[ ],[ ],kaiser(128,5))

uses 256 as the value for nfft and 2 as the value for fs.

Txy = tfe(x,y,...,'dflag') specifies a detrend option, where 'dflag' is

- 'linear', to remove the best straight-line fit from the prewindowed sections of x and y
- 'mean', to remove the mean from the prewindowed sections of x and y
- 'none', for no detrending (default)

The 'dflag' parameter must appear last in the list of input arguments. tfe recognizes a 'dflag' string no matter how many intermediate arguments are omitted. tfe(...) with no output arguments plots the magnitude of the transfer function estimate as decibels versus frequency in the current figure window.