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ON THE DURATION OF

SEISMIC PULSES

MASTER

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ABSTRACT

The object of this study is to define the concept of signal duration and perform measurements of duration on seismic data.

ERC Band-Pass Filter (BPF) studies show that energy in the neighborhood of a given frequency band persists for only a few cycles within the time history of measured seismograms. This effective number of cycles is defined as duration. It is shown that the seismic disturbances caused by underground nuclear detonations at the Nevada Test Site have an equivalent constant duration of about four cycles, independent of frequency.

CHAPTER 1

INTRODUCTION

This study was initiated in order to investigate not only the maximum seismic amplitudes within a given frequency range but also the duration around that amplitude. Although both duration and amplitude of ground motion are reflected in the Pseudo Relative Velocity curve or spectrum, (PSRV) which is supplied to the structural response contractor, the question of duration has further significance and is quite worthy of study. Two definitions of the duration of a seismic pulse are given here. The first defines duration as the number of cycles required of a sine wave of given frequency to produce the same statistically measured PSRV to BPF (Band-Pass Filter) ratio¹ at that frequency. The second defines the duration of a pulse as the ratio of total energy transport per unit area to the maximum energy flux in a given frequency band. Both are then normalized to a number of cycles using the center frequency of the band. Both definitions prove to give comparable durations.

¹Lynch, R.D., "A Statistical Relationship Between Band-Pass Filter and Pseudo Relative Velocity Spectra," NVO-1163-88, August 9, 1967, Unclassified.

CHAPTER 2

THEORY

2.1 BAND-PASS FILTER (BPF)

Given a seismic trace, $f(t)$, containing a broad spectrum of frequencies, one can transform that trace to another time trace containing a restricted range of frequencies around some ω_o by utilizing a narrow band-pass filter centered at ω_o . The resulting time history, $f_b(t)$, will be a trace retaining that portion of the input trace having frequencies comparable with $\omega_o/2\pi$. The amplitude is representative of the amplitude of waves seen in $f(t)$ having that frequency. ERC utilizes such a filter with a transfer function given by

$$F(s) = \left[\frac{s\omega_o}{s^2 + \omega_o^2 + s\omega_o} \right]^4$$

(s = the Laplace transform variable), and its realization on an analog processor is shown by the circuit in Figure 1.

Figure 1. Band-Pass Filter Analog Computer Diagram.

2.2 PSEUDO RELATIVE VELOCITY PSRV(t)

The structural response contractor uses the response to ground motion of a single degree of freedom system (mass-spring system with velocity damping) in its data analysis program. Two parameters, resonant period $P_o = 2\pi/\omega_o$ and damping factor h , characterize this system. The transfer function $F(s)$ relating output, PSRV(t), to input ground velocity, $f(t)$, is given by

$$F(s) = \frac{s \omega_o}{s^2 + \omega_o^2 + 2h \omega_o s}$$

where s is the Laplace transform variable. The realization of an electrical analog circuit having the above transfer function is shown in Figure 2. Typical values of h are 0.02, 0.05 and 0.10.

2.3 BPF AND PSRV SPECTRA

BPF and PSRV spectra are respectively defined as the peak filter output vs filter center frequency or period. That is

$$\text{BPF spectrum} = \left| f_b(t) \right|_{\text{MAX}} (\omega_o)$$

and,

$$\text{PSRV spectrum} = \left| \text{PSRV}(t) \right|_{\text{MAX}} (\omega_o)$$

Figure 2. Pseudo Relative Velocity Analog Computer Diagram.

Both BPF and PSRV spectra are used at ERC to study amplitude-frequency information about nuclear-generated seismograms; BPF spectra are a direct characterization of the ground motion, whereas PSRV spectra characterize both the ground motion and its effect on certain mechanical systems.

For velocity seismograms recorded at 48 to 173 km, PSRV and BPF spectra have been obtained at a sufficient number of frequencies to define continuous spectra over the frequency range from 0.41 to 11.3 Hz. A typical example is given in Figure 3. It can be seen that the two spectral curves are approximately "parallel" over the entire period range and that multiplication of the BPF curve by some factor would represent a "smoothed" PSRV curve.

2.4 DURATION

Consider a sine wave having a number, d , of cycles at fixed amplitude. We will say the duration is d cycles. The BPF output and PSRV output for $h = 0.02$, of such a wave are shown in Figure 4. Note that the BPF output for 2.5 cycles or more input reaches maximum amplitude equal to the maximum amplitude of the input sine wave, but that the PSRV output builds up in amplitude with duration. This build-up persists in the limit of zero damping. The envelope of maximum amplitude for both PSRV ($h = 0.02$) and

Figure 3. Measured Pseudo Relative Velocity and Band-Pass Filter Spectra

$f(t) = \text{INPUT}$

$f_b(t) =$
BPF OUTPUT

PSRV(t) =
PSRV OUTPUT
(2% DAMPING)

Figure 4. Transient Response of BPF and PSRV (2%) to Sine Wave Input.

BPF outputs as a function of duration is shown in Figure 5. As observed in Section 2.3, the PSRV spectra and BPF spectra parallel each other. In Chapter 3 we show that this phenomenon is a consequence of a frequency-independent duration. The duration is defined in Chapter 3 using Figure 5 and a statistically determined ratio of the maximum of PSRV and BPF spectra derived from recorded ground motion.¹

Given the BPF velocity trace around frequency ω_0 of a seismic disturbance, the kinetic energy density in that frequency band is expressed by

$$\text{K.E. density} = \frac{1}{2} \rho v(t)^2$$

and the kinetic energy flux is

$$\text{K.E. flux} = \frac{1}{2} \rho c v(t)^2$$

where $v(t)$ is the BPF particle velocity as a function of time, ρ is the density of the medium and c is the group velocity of the disturbance. The envelope of the K.E. flux time record is the net energy flux, being comprised of the superposition of the kinetic and potential energy fluxes. The maximum energy flux is characterized by the

¹ Ibid.

Figure 5. Envelope of Peak Transient Response of PSRV and BPF

maximum squared amplitude of the BPF particle velocity trace. Now, if one desires the net energy transfer per unit area caused by a seismic pulse in the frequency band of interest then the envelope of the kinetic energy flux must be integrated across the pulse.

$$\text{Net Energy Transfer/Area} = \int_{\text{pulse}} \frac{1}{2} \rho c v_{\text{env}}^2 dt$$

The pulse duration in cycles is now defined as

$$\text{duration} = \frac{1}{2} \cdot \frac{\text{Net Energy Transfer/Area}}{\text{Maximum Energy Flux}}$$

It will be shown by experiments described in Chapter 3 that durations defined in this way are comparable with the definition via the PSRV and BPF maximum amplitudes.

CHAPTER 3

EXPERIMENTS

3.1 BPF VS PSRV

A statistical analysis¹ was made of the observed amplitude ratios between PSRV (2%) spectra peaks and BPF "parallel" spectra for the following events.

1. Rex
2. Chartreuse
3. Duryea
4. Halfbeak.

A total of 1673 ratios from 62 horizontal components recorded at 33 stations were employed. From these data, the mean ratio, $\bar{X}$, and the standard deviation, σ , were computed for (1) each component, (2) each event and (3) all four events.

From the total sample the following results were obtained:

$$\bar{X} = 8.57$$

$$\sigma = 2.45$$

It was also shown that the distribution of the data about the mean $\bar{X}$ is Gaussian (normal). In addition, the results

¹ Ibid.

from each horizontal component and from each event give essentially the same values as from the total sample showing that each subsample is a good representation of the total population. The mean amplitude ratio $\bar{X}$ can be converted to duration by using Figure 5. An amplitude ratio of 8.57 corresponds to a sine wave of unity amplitude with a duration of 3.6 cycles. The duration for $\bar{X} + \sigma = 11.02$ and $\bar{X} - \sigma = 6.12$ are respectively 4.9 and 2.3. Since 68% of the readings fall between $\bar{X} \pm \sigma$, the same percentage would fall between 3.6 cycles $\pm$ 1.3 cycles.

3.2 TOTAL ENERGY/MAXIMUM ENERGY FLUX

Independently, pulses from the BPF time histories were analysed to obtain the total energy transport per unit area and the maximum energy flux for various frequency bands. The duration calculated in this manner is shown in Table 1. Note that the mean duration measured in this way is 3.9 cycles and agrees favorably with PSRV vs BPF measurements. Again it is seen that the variation of duration in seconds is such that the duration in number of cycles is invariant.

TABLE 1. DURATION FROM MAXIMUM ENERGY FLUX

<u>Number</u>	<u>Station</u>	<u>Component</u>	<u>Frequency Hz</u>	<u>Maximum Velocity V_n</u>	<u>V_n^2</u>	<u>Duration Time (sec)</u>	<u>Duration, d, Number of Cycles</u>
1	SE-6	N/S	0.41	8.5	72.3	9.70	3.94
2	SE-6	N/S	0.41	8.2	67.2	8.65	3.50
3	SE-6	N/S	0.55	5.2	27.0	9.69	5.20
4	SE-6	N/S	0.75	11.0	121.0	5.55	4.17
5	SE-6	N/S	0.75	10.2	104.0	4.35	3.22
6	SE-6	N/S	1.00	11.0	121.0	4.69	4.68
7	SE-6	N/S	1.00	7.1	50.4	2.85	2.85
8	SE-6	N/S	1.35	3.5	12.2	2.75	3.70
9	SE-6	N/S	1.85	7.5	56.2	2.84	3.84

$$\text{mean } (\bar{X}) = \frac{1}{n} \sum_{n=1}^N d_i = 3.90$$

$$\bar{X} + \sigma = 4.62$$

$$\bar{X} - \sigma = 3.18$$

$$\sigma = \left[\frac{\sum d_i^2}{N-1} - \frac{1}{N(N-1)} (\sum d_i)^2 \right]^{\frac{1}{2}} = 0.719496$$

CHAPTER 4

CONCLUSIONS AND RECOMMENDATIONS

Over the frequency range of 0.41 to 11.3 Hz duration of seismic waves has been found to be constant, slightly under four cycles, for ground velocity generated by several underground NTS nuclear detonations. It appears remarkable indeed that the duration in cycles should be frequency independent. There is no physical understanding of this phenomenon at present but perhaps it is a consequence of the nuclear detonation and/or the statistical nature of the medium (earth).

It is presently recommended that these results be reviewed by the structural response contractor and that discussion be subsequently initiated.