Pulse Coding in Seismology

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Preface

Coding is used in a number of techniques that derive from communication theory. Let us take the case of the telephone line, for instance, where the transmission medium is known. Thanks to coding, a single line can pass several independent messages simultaneously, thus improving the economics of the line. In seismic work the transmission medium is unknown, but the comparison of the output received signal with the input transmitted signal gives some information about this transmission medium. The more discrete messages transmitted at the input, the better the subsurface will be known. The faster these discrete messages are transmitted, the lower the price for the information.

A seismic message will be coded if, due to the energy transmission, the signals received by the geophones cannot be interpreted without applying a special process called decoding.

According to the above definition, two types of seismic coding exist. The first was developed by Conoco more than twenty years ago and commercialized under the trademark of Vibroseis. The coded signal is continuous and is sent into the earth using vibrators firmly coupled to the ground. The second type is represented by systems recently designed by Société Nationale ELF Aquitaine, Production—SNEA (P). In this case any pulse seismic source can be used, e.g., a civil engineering rammer. In the case of Mini-Sosie, the code consists of a series of different time intervals between the transmitted pulses. It is therefore a discontinuous coded signal.

There are at least two reasons to justify the use of seismic coding. The first one is the possibility of increasing the transmitted energy by exploiting the parameter of the length of transmission instead of the peak power of the source. The consequent energy increase is obtained without any loss of resolution on the final seismogram. A vibrator can transmit a sweep of variable length without affecting the shape of the autocorrelation function of this signal. Only the amplitude changes. A pulse source, when used with a coded system, can be fired as often as its specifications allow without being obliged to leave a listening time after each pulse. It is only the shape of the individual pulse which must be considered with regard to the resolution.

A second reason to justify coded systems is the possibility of separately processing several streams of seismic data which have been simultaneously recorded through the same seismic channel. More information can then be obtained during the same recording time and with the same receivers and recorder.

Difficulties arise when using coded systems. The most important one is the existence of correlation noise. Another one is the strong requirement to make the transmitted signal similar to the code.

The existence of correlation noise may degrade the quality of the results in the same way as any other type of noise, e.g., instrument noise or ambient noise. However, there are two types of correlation noise. The first one is caused by the mathematics of the code, and the second one takes into account the physical systems, including the earth, that are used in field operations.

The requirement to make the transmitted signal as similar as possible to the code applies mainly to continuous signal coding. In the case of pulse coding only the zero time of each transmitted pulse is considered.

Pulse coding is a relatively new technique whose only field application is the Mini-Sosie system. Eventually, other applications using more powerful sources will be designed.

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Introduction

Historical Development

The first coded method used in seismology was the Vibroseis method. Proposed in 1958 by the Continental Oil Company, the Vibroseis method is an application to seismology of a principle already used in Radar Technique known as Chirp Radar. In the early 1960s, another system was proposed by Rogers Exploration Inc. under the trademark of Rogacord. In both cases, seismic energy is transmitted by vibrators coupled to the ground, sending continuous signals into the earth. In the case of the Vibroseis method, this signal is a sine wave, the frequency of which is linearly varying with time. This is called a sweep. In the case of the Rogacord method, the signal is a portion of a sine wave at a given frequency.

The main characteristic of coded seismology is that the data recorded by the geophones cannot be interpreted as they are received because they show a complete lack of resolution, and the different reflections overlap each other. To obtain useful results, a special processing, called the decoding process, is needed. In the Vibroseis method, decoding consists of crosscorrelating the received data with the transmitted sweep. In this case the final seismic record is the same as if the autocorrelation of the sweep had been transmitted (Fig. 1). In the Rogacord method, decoding consists of summing different records obtained by successively transmitting different fixed frequencies. In this case again the final record is the same as if the sum of the fixed frequencies were transmitted at once (Fig. 2).

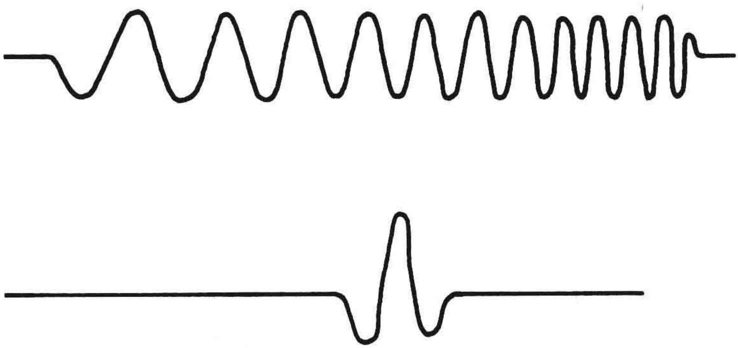

Figure 1 Vibroseis method: sweep and its autocorrelation.

Continuous Transmission of Discrete Pulses

Another idea was proposed in coding seismology which consisted of transmitting a sequence of pulses in order to generate a composite signal with a particular envelope. This was in effect the transfer to seismic transmission of what is done during the seismic reception with digital recording (Fig. 3). Because it is difficult to control the amplitude of a transmitted seismic pulse and impossible to transmit large negative pulses, the signal is transmitted as shown in Figure 3.

No serious tests have been made with this method. One reason for this is that it is difficult to find a seismic source that can produce pulses with a high enough rate of repetition. Probably sparkers are the only sources able to produce the required rate of repetition, if the energy of each spark is low enough and it is possible to incorporate several sparkers at the same time.

There is, in fact, another reason to doubt whether it would work. A seismic pulse is not a positive spike but a positive

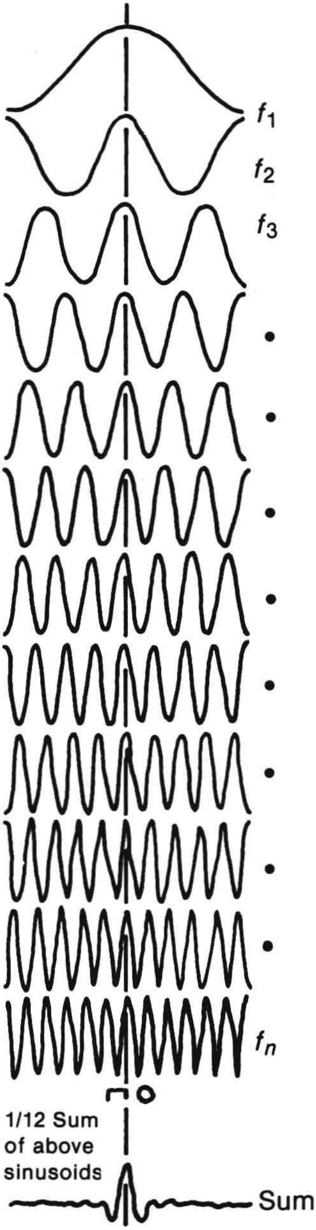

Figure 2 Rogacord: fixed frequencies and their sum.

elongation followed by a negative one (Fig. 4). Because there is no D.C. component in a seismic pulse, you cannot expect to produce with several pulses a lower frequency than the lowest frequency present in each pulse. Therefore, if we have to use many pulses of low energy we cannot expect to produce low frequencies.

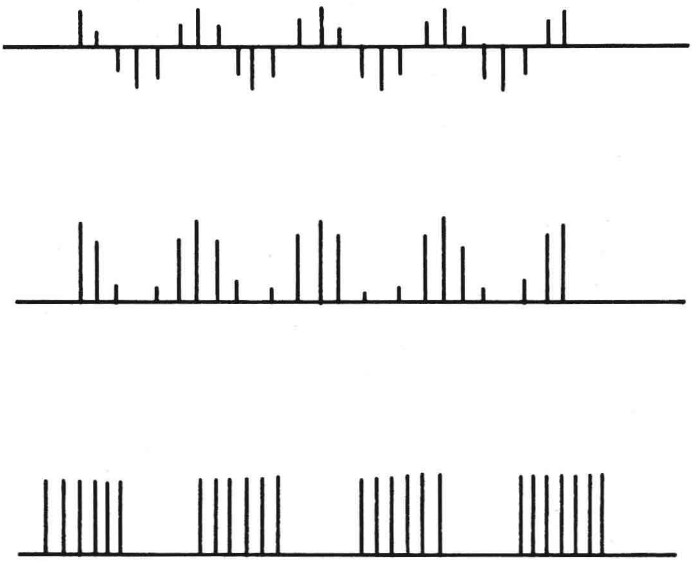

Figure 3 Continuous transmission of discrete pulses.

Pulse Coding

Several different patents on pulse coding systems have been filed and registered. (Only some of them will be described.) What was the reason for these ideas? At the time the patents were filed, the method that was used was called *normal seismology*. This method consists of transmitting one short pulse produced by explosive or mechanical sources, and recording the seismic data received by geophones or hydrophones for a period of time called the record time. Another well-known

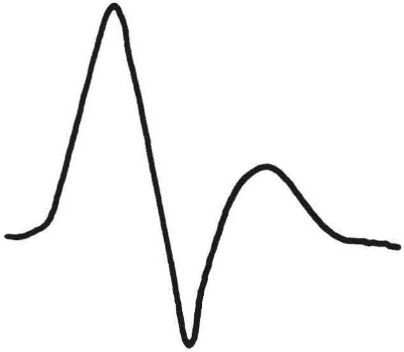

Figure 4 Seismic pulse.

method that was used at the time was called the Vibroseis method.

Any pulse coding method can be seen as a combination of these two methods: a transmission of short pulses like the normal method and a transmission of a long coded signal like the Vibroseis method. However, there will of course be some important differences. There will not be just one pulse per record time like the normal method, but a sequence of at least two of them. The coded signal will not be continuous, but will be comprised of a series of discrete pulses. Therefore, instead of using a vibrator resting on the ground and transmitting a continuous signal like a sweep, we must use one or more sources transmitting discrete pulses for a given time. This is called a sequence. Sparkers, Vaporchoc, air guns, Aquapulse, Dinoseis, Thumpers, and most recently civil engineering rammers, have been either tested or used as seismic sources with pulse coding systems. Even vibrators can be used, because after correlation the signal which has been transmitted can be considered as the autocorrelation function of the sweep which is equivalent to a pulse (the Klauder wavelet). The polarity of the correlated pulse depends on the relative phases of the transmitted sweep and the reference sweep. Therefore, after correlation, it can be considered that a given vibrator has transmitted either a large positive or a large negative pulse. We can say that vibrators are the only sources that can transmit large negative pulses.

The fact that a pulse coding technique is a combination of the normal method and the Vibroseis method is not a good enough reason to justify it. For example, some people will probably argue that this new technique will have the disadvantages of both methods. Let us say that pulse coding will complement the others with some specific applications.

Applications

When compared with the normal method using explosives, the Vibroseis method proves to be more advantageous when the drilling is difficult because of the lower cost per mile. There is also a higher degree of multiplicity. That is to say, more discrete raypaths, producing better seismic results. Let us note that the limit to the degree of multiplicity has not yet been reached since more and more recording channels are at present being introduced. We shall see later on that pulse coding can increase the number of seismic channels without increasing the number of recording channels.

There are problems when the Vibroseis method is applied to marine seismology. A seismic boat, for example, does not spend enough time at each shot point to transmit several long sweeps. It takes only a little more than 15 seconds for a boat to move 50 meters and this is less than one normal sweep length on land. This is the reason why a pulse coding technique was first designed for marine applications. The number of discrete pulses transmitted in the time available is unlimited if the energy per pulse is accordingly reduced. On the boat there is a power generator able to deliver one pop of high energy approximately every six seconds, the record length of the final seismogram. By definition, pulse coding allows delivery of more than one pop per record length; but the energy per pop is then reduced due to the specifications of the power generator.

The application of the Vibroseis method to shallow seismology, let us say less than 500 ms twt, faces economical problems. A vibrator is a sophisticated and expensive seismic source. Because the required crosscorrelation is generally performed in a processing center, it increases the cost when compared with the normal method. Even if correlation is performed in the field, the recording instruments are more expensive than the instruments used for normal recording. This is why a pulse coding technique is successful in this seismic domain. Pulse coding applied to shallow seismology will use a rather inexpensive source; and decoding is performed in real time so that the tapes that are to be processed are like normal method tapes. The instruments necessary for applying a real time decoding are similar to the normal stackers used for the normal method.

A pulse coding technique should also be used whenever there is a problem in synchronizing several sources. This is the case with the Thumper. A pulse coding technique has been designed to allow operators simultaneously to use several Thumpers.

Time and Space Coding

Let us add some remarks about further possible applications which will illustrate that the coding technical domain is extremely powerful.

A seismic section or a seismic record is a function of time and space (t,x). We know that any parameter in the time domain, like sample interval or time period, has its equivalent in the space domain, trace interval, and wavelength. In field operations we are used to sources synchronized with an accuracy of better than half the sample rate. We are also used to designing source patterns, which is nothing but the introduction of a time interval between the arrivals at a given geophone station of the two pulses produced by two sources in a pattern. As is well known, the time interval will depend on the distance between the two sources and the apparent velocity of the recorded events (Fig. 5). This operation could be called *space coding* because we use the x parameter to produce a time interval between the same type of seismic event generated by two sources. The advantage of this space coding operation is an improvement of the signal to horizontally travelling noise ratio.

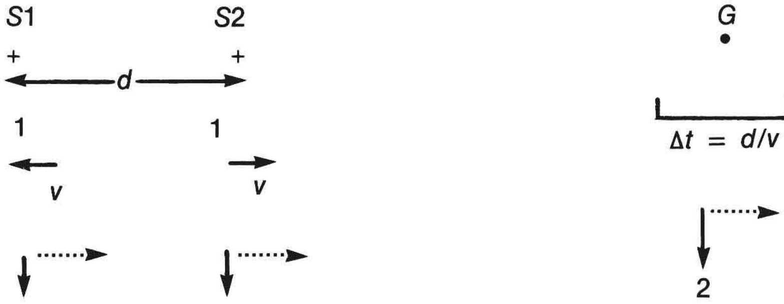

Figure 5 Two synchronized sources, S_1 and S_2: A horizontally travelling event will be convolved with a two-point operator; a vertically travelling event will have its amplitude multiplied by two.

The price paid for this is a loss of resolution because the two pulses will then be in phase only if the seismic event has an infinite apparent velocity. This, however, is never the case.

If there exists a coding operation using the x parameter then there also exists a coding operation using the t parameter. *Time coding* will correspond to one source (or two sources at the same location) sending two pulses into the ground, the two pulses being separated by a time interval. Let us note that to produce a time interval between two seismic pulses it is the x parameter and not the t parameter that was first used— the reverse of what might be expected. It is the time coding of pulses which will be discussed in this book. Time coding or rather *pulse coding* will allow more known information to be put into the ground at a given time with the intention of finding out more about this ground. The price paid for this advantage will be the presence of correlation noise.

From the time-space *(t,x)* domain of a seismic section we can pass to the frequency-wave number *(f,k)* domain using the Fourier transform. In this new domain it is easier to understand time-frequency filtering, space-frequency filtering, and therefore velocity filtering. By analogy we can say that if space coding and time coding exist, we can imagine a time-space coding whereby, adding some time coding (i.e., pulse coding) to the well-known space coding (pattern design), we might improve the wave number *(k)* filtering without using patterns that are too long.

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Marine Pulse Coding: Sosie

Definition

Sosie is the trademark of a pulse coding technique designed by SNEA(P) for marine seismology. It is an abbreviation of the French expression *So*urce *si*smique *e*chantillonnée which in English means *sampled seismic source.* The reason for this name is that digital recording technology had just been introduced in Europe. With the Sosie method, one or more sources transmit pulse sequences, i.e., more than one pulse is transmitted by each source during each record time.

The Sosie principle was first tested using a sparker as a seismic source. The first results were presented in a paper at the SEG meeting of November 1970 and published in *Geophysics* (Barbier and Viallix, 1973). Later on Vaporchoc was tested and then air guns were used for routine operations on some exploration programs.

Characteristics

Energy is transmitted at moments fixed by the Sosie sequence and expressed by the following mathematical formula:

$$y = \sum_{i=1}^{i=n} \delta(t - t_i) \quad (1)$$

where n is the number of pulses in the sequence.

$\delta(t - t_i) = 1$, when $t = t_1, t_2, \ldots t_i, \ldots, t_n$,

$\delta(t - t_i) = 0$, the rest of the time.

If we call T the maximum reflection time or the record time when only one pulse is released, then the Sosie sequence is much longer than T, and the time interval between two successive pulses is much shorter than T. These two conditions can be expressed as:

$$(t_{i+1} - t_i) < T < t_n$$

t_n being the time at which the last pulse of the sequence is produced. This is a measure of the duration of the Sosie sequence.

The number, n, of the pulses and the time intervals between the pulses are such that the autocorrelation function of the sequence computed over a length of $2T$ seconds has a central spike of much higher amplitude than the secondary peaks which appear symmetrically relative to the maximum central spike. This autocorrelation function can be expressed as:

$$\int_{-T}^{+T} y(t)y(t+\Theta)dt$$

where Θ is the time shift in the autocorrelation process and it consists of a central spike of amplitude, n, if the amplitude of each pulse is taken as 1, and $n(n-1)$ secondary peaks of amplitude 1 over the whole length equal to $2t_n$ of the theoretical autocorrelation function. The number of secondary peaks over the length $2T$ depends on the relative values of T and the time intervals between pulses.

All these secondary peaks form the correlation background noise. The $n(n-1)$ peaks do not necessarily appear at different times. When two peaks appear at the same time, the amplitude at this time is 2. If three peaks coincide, the amplitude is 3, and so on.