Chapter 3

Seismic instrumentation

In this chapter we discuss the different instrumentation components as used for gathering seismic data. It discusses briefly these components as typically used in seismic exploration: the seismic sources (airgun at sea and dynamite and the so-called vibroseis source on land), the seismic sensors (hydrophones at sea and geophones on land) and the seismic acquisition system. The effects of these components can usually be directly observed in the seismic records, and the aim of this chapter is that the reader should become aware of the contribution of these components. (For the readers with a background in signal analysis, the effects are quantified in terms of signals and Fourier spectra.)

3.1 Seismic data acquisition

The object of exploration seismics is obtaining structural subsurface information from seismic data, i.e., data obtained by recording elastic wave motion of the ground. The main reason for doing this is the exploration for oil or gas fields (hydro-carbonates). In exploration seismics this wave motion is excitated by an active source, the seismic source, e.g. for land seismics (onshore) dynamite. From the source elastic energy is radiated into the earth, and the earth reacts to this signal. The energy that is returned to the earth's surface, is then studied in order to infer the structure of the subsurface. Conventionally, three stages are discerned in obtaining the information of the subsurface, namely data *acquisition*, *processing* and *interpretation*.

In *seismic data acquisition*, we concern ourselves only with the data gathering in the field, and making sure the data is of sufficient quality. In seismic acquisition, an elastic wavefield is emitted by a seismic source at a certain location at the surface. The reflected wavefield is measured by receivers that are located along lines (2D seismics) or on a grid (3D seismics). After each such a *shot record* experiment, the source is moved to another location and the measurement is repeated. Figure 3.1 gives an illustration of seismic acquisition in a land (onshore) survey. At sea (in a marine or offshore survey) the source and receivers are towed behind a vessel. In order to gather the data, many choices have

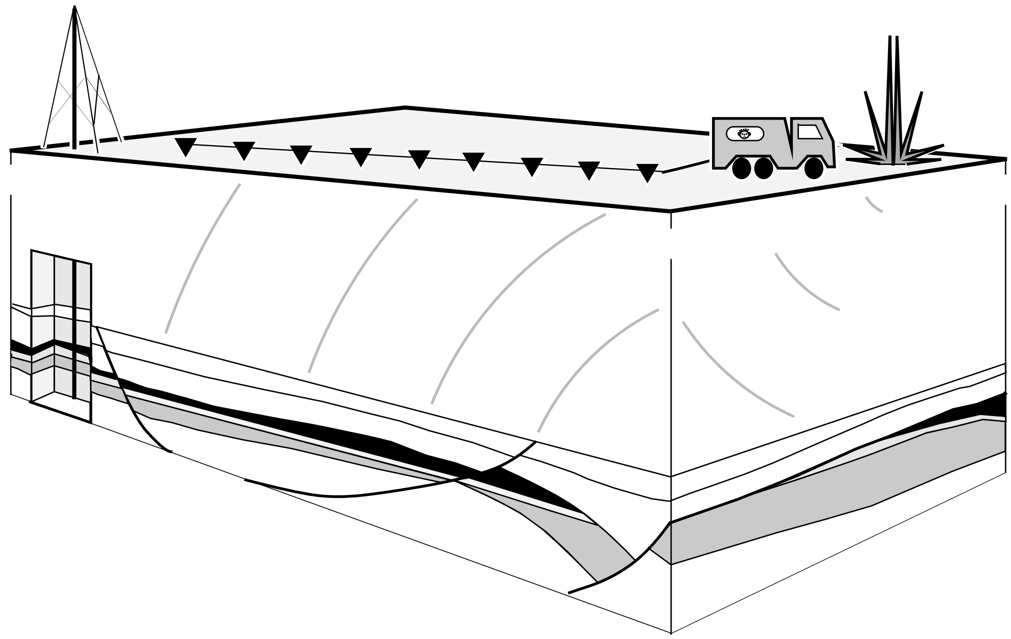

Figure 3.1: Seismic acquisition on land using a dynamite source and a cable of geop hones.

to be made which are related to the physics of the problem, the local situation and, of course, to economical considerations. For instance, a choice must made about the seismic source being used: on land, one usually has the choice between dynamite and vibroseis; at sea, air guns are deployed. Also on the sensor side, choices have to be made, mainly with respect to their frequency characteristics. With respect to the recording equipment, one usually does not have a choice for each survey but one must be able to exploit its capabilities as much as possible.

Various supporting field activities are required for good seismic data acquisition. For example, seismic exploration for oil and gas is a complex interaction of activities requiring good management. Important aspects are:

- General administration/exploration concession and permit work (”land and legal”); topographic surveying and mapping, which is quite different for land- or marine work.
- More specific seismic aspects: placing and checking the seismic source, which on land is either an explosive (for example dynamite) or Vibroseis and at sea mostly an array of airguns; positioning and checking the detectors, geophones on land, hydrophones at sea; operating the seismic recording system.

The organisation of a seismic land crew, often faced with difficult logistics, terrain- and access road conditions is quite different from that of marine seismic crew on board of an exploration vessel, where a compact streamlined combination of seismic and topo operations is concentrated on the decks of one boat; different circumstances require different strategies and different technological solutions.

This chapter deals with seismic instrumentation, i.e., all the necessary hardware to make seismic measurements in the field.

First of all, we have to generate sound waves, with sufficient power and adequate frequency content in order to cause detectable reflections. This will be discussed in the section on sources. Then, when the waves have travelled through the subsurface, we want to detect the sound, and convert the motion to an electrical signal. This will be discussed in section on geophones and hydrophones. Then, the electrical signal is transported via cables to the recording instrument where it will be converted such that it can be stored, usually on tape, and can be read again at a later time. This is necessary when we want to process the data to obtain a seismic image of the subsurface. Recording systems are discussed in the section of recording systems.

The general model which is assumed behind the whole seismic system, is that all the components are linear time-invariant (LTI) systems. This means that the digital output we obtain after a seismic experiment in the field is a convolution of the different components, i.e.,:

$$x(t) = s(t) * g(t) * r(t) * a(t) \tag{3.1}$$

in which

$$\begin{aligned} x(t) &= \text{the seismogram (digitally) on tape or disk} \\ s(t) &= \text{the source pulse or signature} \\ g(t) &= \text{the impulse response (or Green's function) of the earth} \\ r(t) &= \text{the receiver impulse response} \\ a(t) &= \text{the seismograph impulse response (mostly A/D conversion)} \end{aligned}$$

As may be obvious, in each of the following sections, we will discuss each of these impulse responses, apart that from the earth, since that is the function we would like to know at the end. That will be part of the chapter on processing.

3.2 Seismic sources

This section deals with the seismic source. The source generates the (dynamical) mechanical disturbance that cause a seismic wave motion with a characteristic signal shape ("signature") to travel through the subsurface from source to receivers. The seismic source has a dominant influence on the signal response resulting from the total acquisition system, i.e. the response due to source, receiver(s) and seismic recording system. In this chapter the seismic sources as routinely used by the oil industry in the exploration for oil and gas will be treated: airguns as used in marine operations, Vibroseis and dynamite as used for seismic operations on land. For each type of source the most important aspects of the mechanical principles of operation will be treated and then the characteristic seismic signal produced by the source (the source's "signature").

3.2.1 Airguns

Many oil and gasfields are found in water-covered areas, such as the Gulf of Mexico and the North Sea. Ever since the 1960's companies were not allowed to use dynamite any more as seismic source because of fish dying massively due to the sharp and destructive strong shockwave from the dynamite. Exploration companies had to look for alternatives. Many sources were developed since then, such as airguns, waterguns and even a marine equivalent of the Vibroseis. Airguns became the most popular marine source in the oil industry because of their renowned reliability and signature repeatability. The signature of one airgun has an inconveniently long and oscillatory character, the reason why airguns are used in specifically designed arrays, consisting of airguns with different volumes.

The mechanics of the airgun

As is obvious from the name, the driving mechanism of the airgun is supplied by (compressed) air. In Figure (3.2) we have given a schematic view of an airgun. Air under pressure is pumped into a chamber. Using the piston, the air is suddenly released and the air leaves the chamber and starts to create a bubble in the surrounding water. Inside the bubble we have the air but there is a turbulent region which consists of many little bubbles, the non-linear zone. This is schematically given in figure (3.3) (a). The mechanism behind the behaviour of the airgun is depicted in figure (3.3) (b) and (c). The bubble increases in the beginning but after a while the pressure from outside, the hydrostatic pressure, is larger than the pressure from inside of the bubble and the expansion slows down. The expansion comes to an end and the bubble reaches its maximum radius when the kinetic energy of the outward moving water is fully converted into potential energy related to bubble radius, hydrostatic pressure and some heat losses. From there on, the bubble starts to collapse since the hydrostatic pressure from outside is larger than the pressure inside. The collapse slows down when we have again passed the equilibrium position (where the pressure inside the bubble is equal to the hydrostatic pressure) until we have reached a minimum radius where it will start to expand again, and so on.

The collapses and expansions will not go on forever because of the heat dissipation

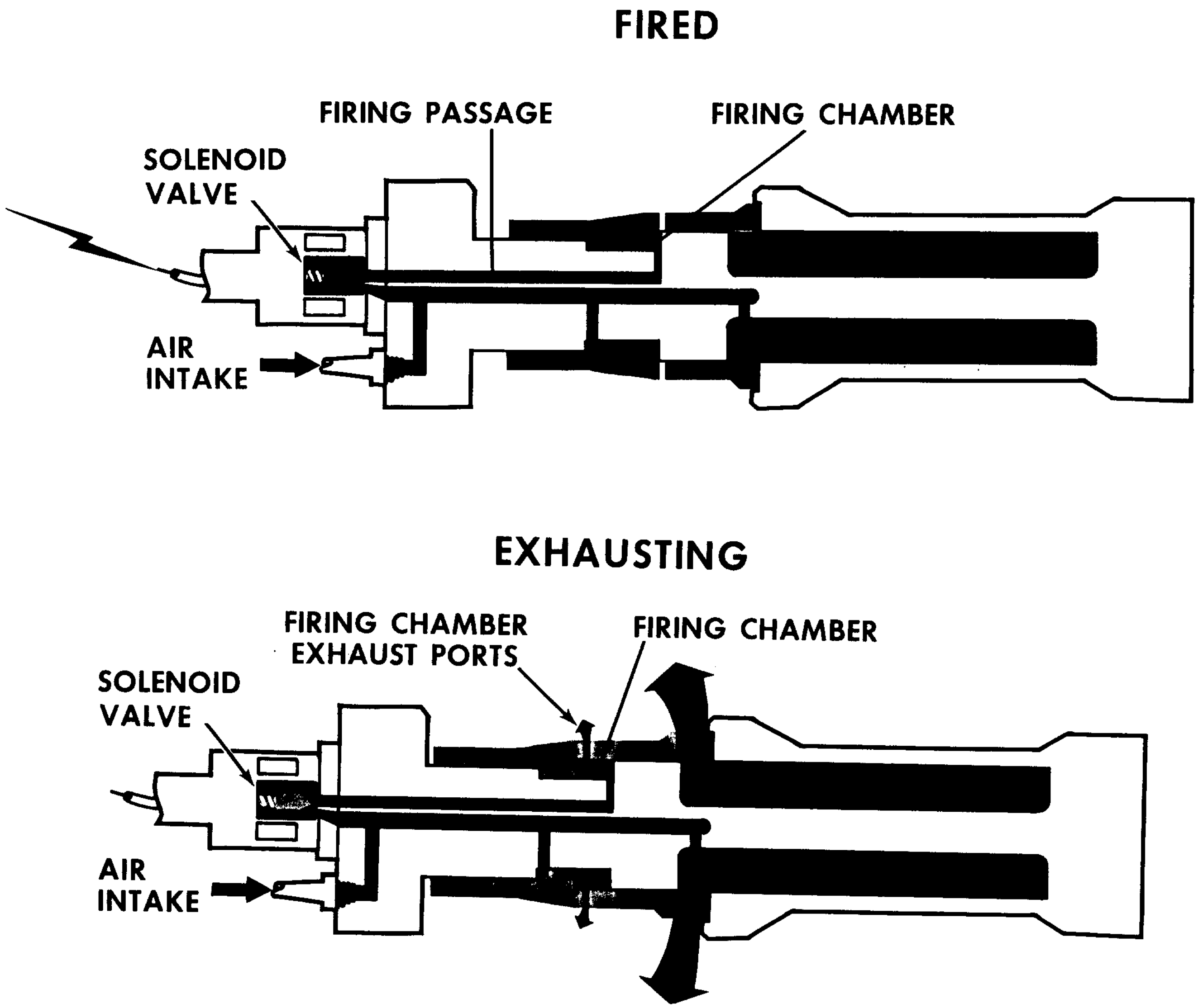

Figure 3.2: Cross-section of an airgun just when it is fired, and when the air is released.

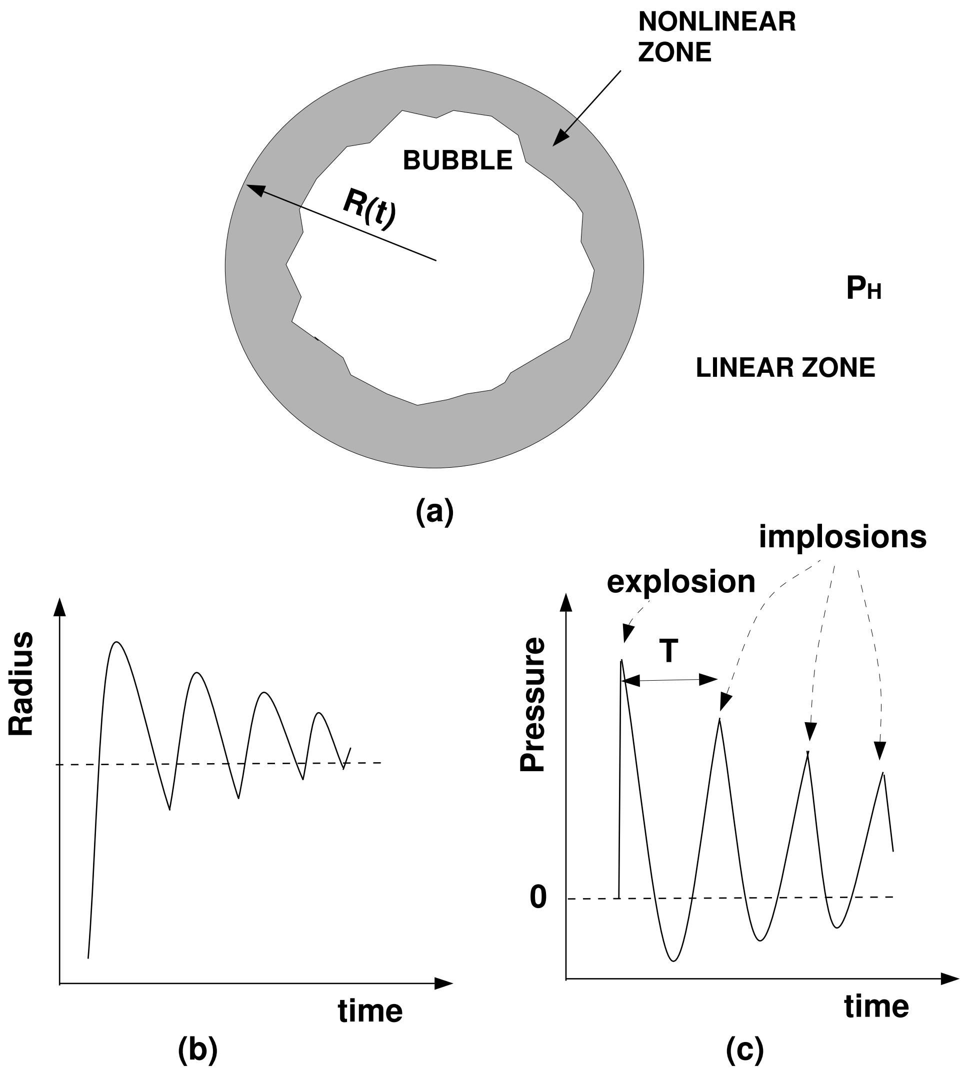

Figure 3.3: (a) Schematic section of the released air bubble; the radius (b) and the pressure (c) as a function of time for the air bubble of an airgun.

into the water. The result from this behaviour is a damped oscillatory pressure signal, somewhat similar to a damped sine curve. The behaviour is depicted in the figure (3.3) (b) and (c), where both bubble radius and the pressure have been plotted as a function of time.

The signal from an airgun

The signal from a single airgun has a length of some 200 ms. Of course, this depends on the type of airgun and the pressure of the air supplied to the airgun. The larger the size, i.e. airgun airchamber volume, or the higher the pressure the longer the period in the oscillations (or, the lower the frequency content). Common pressures are 2000 and 3000 psi. The gun sizes are specified airchamber volume. Common values are 10, 20, 30 up to 100 cubic inches. Much used by many contractors these are the so-called sleeve guns. With the sleeve gun, as the name suggests, the air escapes via a complete ringed opening.

The signature resulting from one airgun is an oscillatory signal which does not resemble the ultimate goal: creating a short seismic signature, preferably a delta pulse. This is the main reason why arrays are used. Airguns of different sizes and at different distances from each other are used such that the first pressure peaks coincide but the other peaks cancel, i.e., destructive interference for the other peaks. Usually with the design of airgun arrays, the largest gun is chosen to give the desired frequency content needed for a survey. Then smaller guns are used to cancel out the second, third, etc. peaks from this large gun. This is done in the frequency domain rather than in the time domain: a delta pulse in time corresponds to a flat amplitude spectrum in frequency. This has resulted in a few configurations of airgun arrays of which the so-called Shell array is the mostly used one. This array has seven guns in one array. The quality of an array is measured via the so-called primary-to-bubble ratio, that means the ratio between the first peak and the second-largest peak. An example of such a signature is given in Figure (3.4). These days P/B ratios of 16 can be achieved.

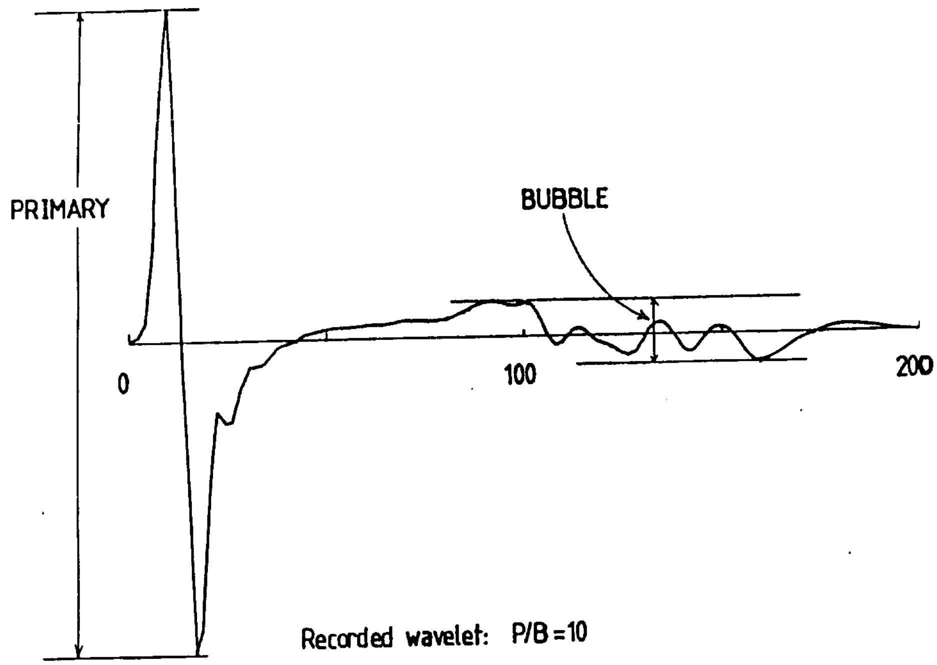

Figure 3.4: Far-field wavelet of tuned air-gun array.

3.2.2 Vibroseis

In seismic exploration, the use of a vibrator as a seismic source has become widespread ever since its introduction as a commercial technique in 1961. In the following the principles of the Vibroseis[1] method are treated and the mechanism which allows the seismic vibrator to exert a pressure on the earth is explained. The basic features of the force generated by the seismic vibrator is discussed: the non-impulsive signal generated by a seismic vibrator having a duration of several seconds. Finally, the advantages and disadvantages of Vibroseis over most impulsive sources are discussed.

The vibrator is a surface source, and emits seismic waves by forcing vibrations of the vibrator baseplate which is kept in tight contact with the earth through a pulldown weight. The driving force applied to the plate is supplied either by a hydraulic system, which is the most common system in use, or an electrodynamic system, or by magnetic levitation. The direction in which the plate vibrates can also vary: P wave vibrators (where the motion of the plate is in the vertical direction) as well as S wave vibrators (vibrating in the horizontal direction) are used. Finally, a marine version of the seismic vibrator has been developed, however not in frequent use. For all these vibrator types, the general principle which governs the generation of the driving force applied to the plate (usually referred to as the baseplate) can be described by the configuration shown in Figure (3.5). A force F is generated by a hydraulic, electrodynamic or magnetic-levitation system. A reaction mass supplies the system with the reaction force necessary to apply a force on the ground. The means by which this force is actually generated is illustrated in Figure (3.6),

[1]Registered trademark of Conoco Inc.

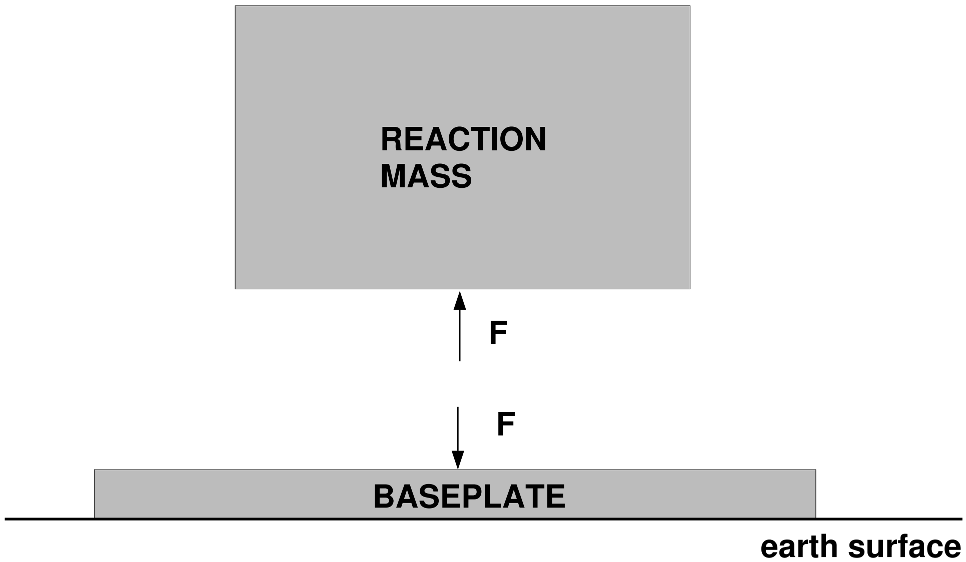

Figure 3.5: The force-generating mechanism of the seismic vibrator source.

in which the principle of the hydraulic drive method is shown. By pumping oil alternately into the lower and upper chamber of the piston, the baseplate is moved up and down. The fluid flow is controlled by a servo valve. The driving force acting on the baseplate is equal and opposite to the force acting on the reaction mass, as can easily be inferred from Figure (3.6). In general, the peak force is such that the accelerations are in the order of several g's, so that an additional weight has to be applied to keep the baseplate in contact with the ground. For the hydraulic and electrodynamic vibrators, the weight of the truck is used for this purpose. This weight, commonly referred to as the holddown mass, is vibrationally isolated from the system shown in Figure (3.6) by an air spring system with a low spring stiffness (shown in figure (3.7)), and its influence on the actual output of the system is usually neglected. The resonance frequency of the holddown mass is in the order of 2 Hz, the lowest frequency of operation in Vibroseis seismic surveys for exploration purposes being usually not less than 5 Hz.

The force exerted on the baseplate

The mechanism by which the seismic vibrator applies a force to the baseplate is very complicated, and differs for different vibrators. In this section, the applied force is described using a simplified mechanical model for a hydraulic P wave vibrator.

A model of a compressional wave vibrator is introduced here which describes the different components of the vibrator in terms of masses, springs and dashpots (i.e. shock absorbers). The model, shown in Figure (3.8), contains three masses. These are the holddown mass, which represents the weight of the truck and is used to keep the baseplate in contact with the ground; the reaction mass, which allows the vibrator to exert a force

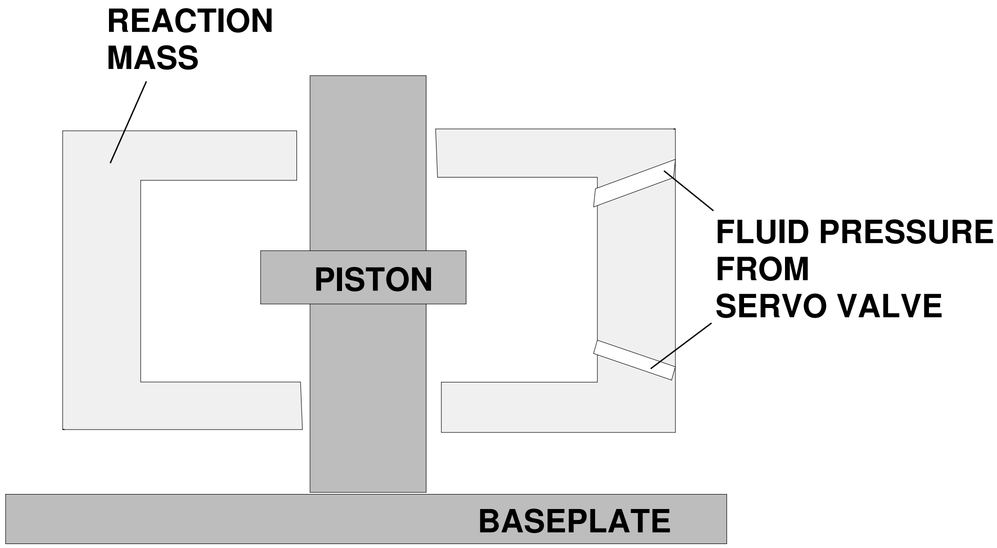

Figure 3.6: Schematic view of the generation of the driving force for a hydraulic vibrator.

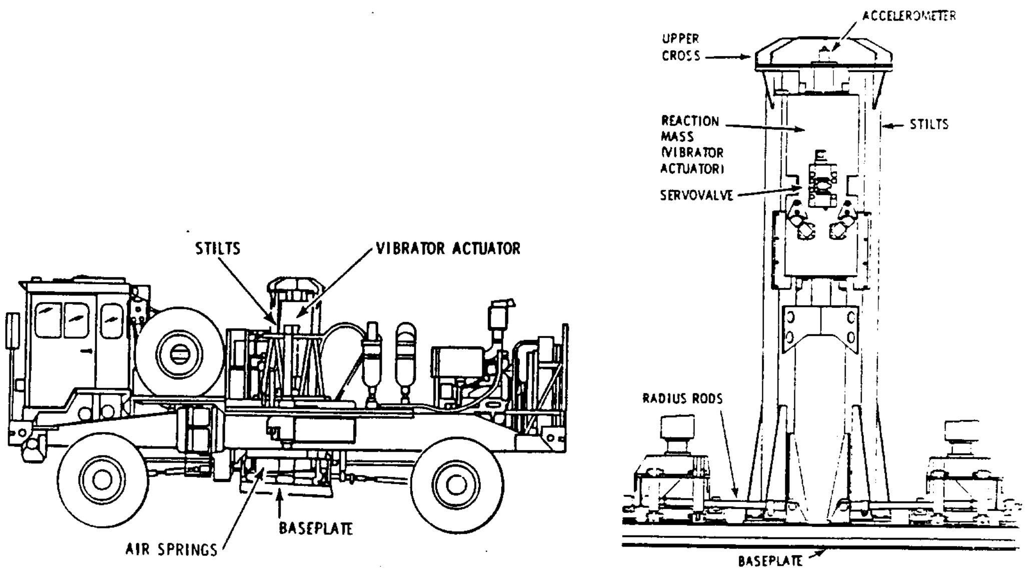

Figure 3.7: (a) schematic view of the Vibroseis truck with the air springs, the baseplate and the vibrator actuator (reaction mass), and (b) detailed view of the middle part of the truck.

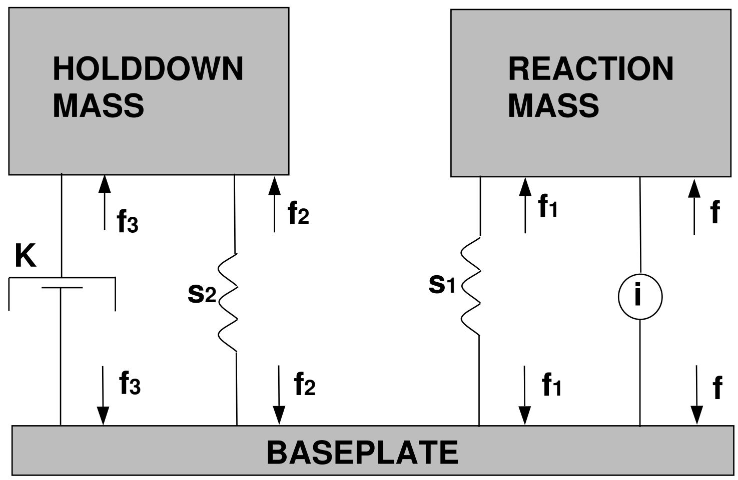

Figure 3.8: The mechanical model of the Vibroseis truck.

on the baseplate; and the baseplate, which is in contact with the earth's surface. The input force i, which is supplied by the vibrator's hydraulic system, is not the same as the force f exerted on baseplate and reaction mass due to the compressibility of the oil pumped in the cylinder. The suspension s_1 represents the means to support the reaction mass in its neutral position. The connection between truck and the baseplate by means of isolated air bags is represented by the dashpot K and suspension s_2. Gravity forces are not included in the analysis because they represent a static load, and do not affect the dynamic behaviour of the seismic vibrator.

The signal emitted by a seismic vibrator

The signal emitted by the seismic vibrator is not impulsive, but typically has a duration of some 10-15 sec. The use of such a relatively long signal seems to be in contradiction with the fact that seismic exploration methods aim at detecting the impulse response of the earth. This apparent contradiction can be clarified by taking a closer look at the properties of an impulse and the earth response to such an impulse.

A perfect impulse at time $t = 0$ contains all frequency components with equal amplitude and zero phase. This is illustrated in Figure (3.9). In practice, one cannot generate a perfect impulse because this would require an infinite amount of energy; the best one can achieve is to emit a bandlimited impulse, resulting in a finite-amplitude wavelet whose time duration is small compared with any dominant signal periods present in the earth's response.

The Vibroseis source emits a bandlimited, expanded impulse. The band limitation has two aspects: at the low frequency end, it is dictated by the mechanical limitations of the

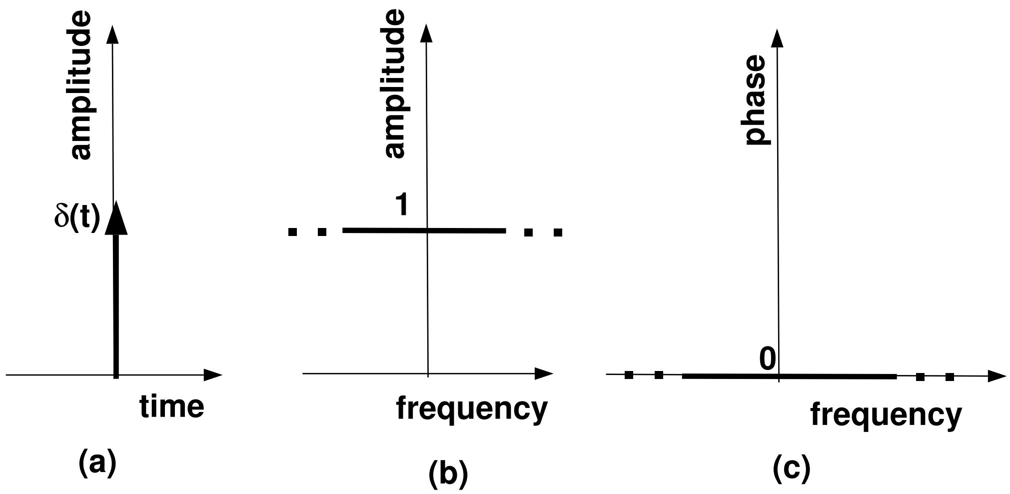

Figure 3.9: The notion of a perfect impulse, (a) in the time domain, and (b),(c) its corresponding frequency domain version.

system and the size of the baseplate. The high frequency limit is determined by the mass and stiffness of the baseplate, the compliance of the trapped oil volume in the driving system for a hydraulic vibrator and mechanical limitations of the drive system.

The notion of an "expanded " impulse can be explained in terms of the amount of energy per unit time, known as energy density. In an impulsive signal, all energy is concentrated in a very short time period, leading to a very high energy density. In the Vibroseis method, a comparable amount of energy is transmitted over a longer time (i.e., smeared out over a longer time), so that the energy density of the signal is reduced considerably. This reduction in energy density is achieved by delaying each frequency component with a different time delay, while keeping the total energy contained in the signal constant. Thus, instead of emitting a signal with a flat amplitude spectrum and a zero phase spectrum, a signal is created which has the same flat amplitude spectrum in the frequency band of interest, however having a non-zero phase spectrum. The frequency-dependent phase shifts cause time delays which enlarge the duration of the signal. However, the total energy of the signal is determined only by its amplitude spectrum (Parseval's theorem!). The effect of the increased time duration of the emission on the recorded seismogram has to be eliminated. This is achieved by having full control of the phase function of the emitted signal. Then, the signal received at the geophone can be corrected for the non-zero phase spectrum of the source wavelet by performing a cross-correlation process of the received seismogram and the outgoing signal (source signal). To clarify this point, let the source wavelet be denoted by $s(t)$. If the convolutional model is adopted to describe the response at the geophone, $x(t)$, the following expression is obtained in the absence of noise:

$$x(t) = s(t) * g(t) \tag{3.2}$$

where $g(t)$ denotes the impulse response of the earth, i.e., the layered geology, and $*$ denotes a convolution. Transforming equation (3.2) to the frequency domain yields

$$X(\omega) = S(\omega)G(\omega) \tag{3.3}$$

If the received signal $x(t)$ is cross-correlated with the source signal $s(t)$, the signal $c(t)$ is obtained which, in the frequency domain, is given by

$$C(\omega) = X(\omega)S^*(\omega) = |S(\omega)|^2 G(\omega) \tag{3.4}$$

since cross-correlation of $x(t)$ with $s(t)$ in the time domain corresponds to a multiplication in the frequency domain of $X(\omega)$ with the complex conjugate of $S(\omega)$. In this equation, the complex conjugate is denoted by the superscript $*$. This cross-correlation is merely a special deconvolution process, in which we exploit the feature that we send out a signal whose amplitude spectrum is constant. This can be seen by looking at the deconvolution as discussed in the chapter on Fourier theory. Applying the deconvolution filter with stabilisation constant amounts to:

$$F(\omega)X(\omega) = \frac{X(\omega)S^*(\omega)}{S(\omega)S^*(\omega) + \epsilon^2}. \tag{3.5}$$

It can be seen here that the numerator is equal to equation (3.4), so the cross-correlation is a partial deconvolution. The main achievement of the cross-correlation is that it *undoes* the phase of the signal. The denominator has the term $S(\omega)S^*(\omega)$. This is a purely real number and therefore only affects the amplitude. In the case that the amplitude is flat, the amplitude does not depend on frequency any more and becomes a simple scaling factor in the deconvolution process. So when the amplitude spectrum of $S(\omega)$ is flat over the frequency band of interest , and zero outside this frequency band, it follows that by cross-correlating the measured seismogram $x(t)$ with the source function $s(t)$, the (scaled) bandlimited impulse response $g(t)$ of the earth is obtained.

In Figure (3.10) the concepts are illustrated for the example of an upsweep, a signal which ends with a larger frequency than it started off with. An 8 sec, 10-100 Hz linear upsweep is used with a taper length of 250 msec. Figure (3.10) (a) shows the sweep. Because the oscillations in the sweep are too rapid to yield a clear picture, the frequency limits for this figure are 1-5 Hz. Figures (3.10) (b) and (3.10) (c) show the amplitude and phase, respectively. It can be observed from these figures that the phase indeed is a quadratic function of frequency, and that the amplitude spectrum of the sweep is constant over the bandwidth. Finally, Figure (3.10) (d) shows the autocorrelation of the sweep.

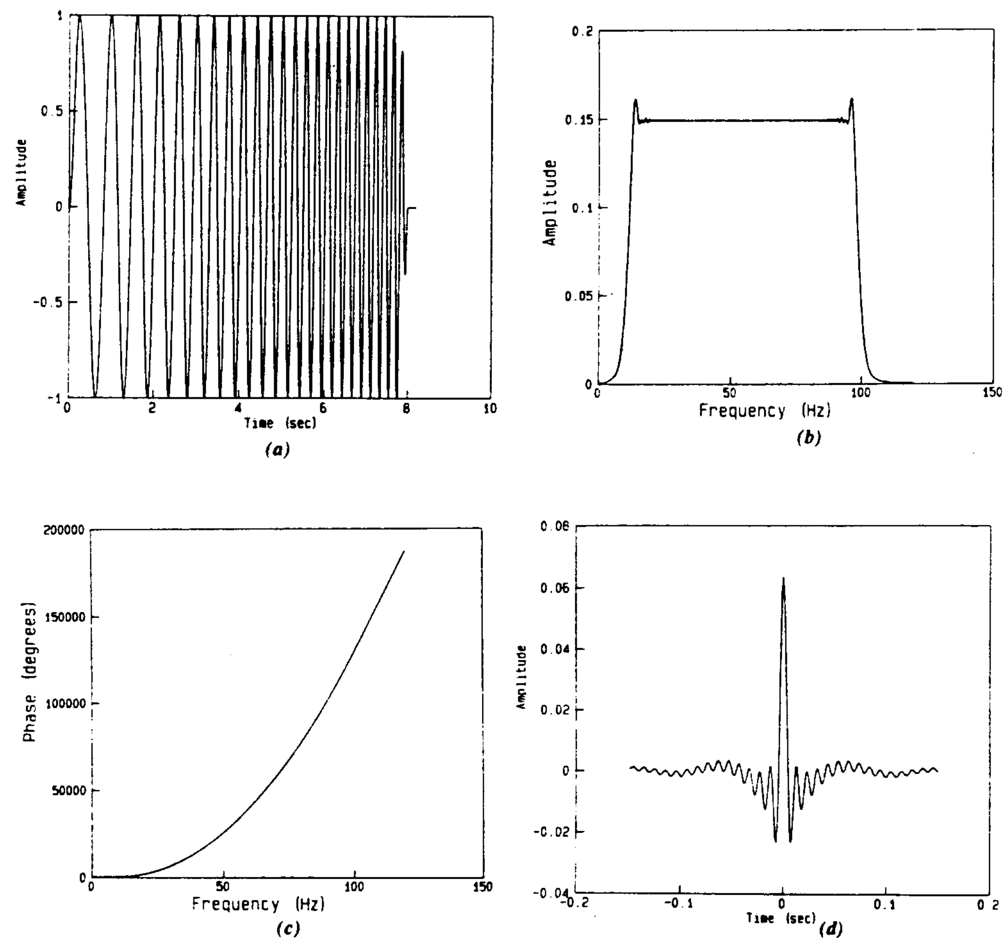

Figure 3.10: An 8 sec, 10-100 Hz upsweep with a taper length of 250 msec. (a) the sweep in the time domain; the frequency range for this Figure is 1-5 Hz for display purposes, (b) the amplitude spectrum of the sweep, (c) the phase spectrum of the sweep, in degrees, and (d) the autocorrelation of the sweep.

3.2.3 Dynamite

Until the arrival of the Vibroseis technique, dynamite was the mostly used seismic source on land. Dynamite itself is very cheap, the costs involved are mainly the costs of drilling the shotholes to place the dynamite. These costs may run up so high as to make the Vibroseis a good competitor of the dynamite source. Dynamite is usually used in non-urban areas for obvious reasons. A nice characteristic of dynamite is that it is resembling a (bandlimited) form of the delta pulse, something we would ideally like to have, since we are interested in the impulse response of the earth. In this section some features of the dynamite source and the signature resulting from it will be discussed.

The chemical working of dynamite and its mechanical impact

Dynamite is a chemical composition which burns extremely fast when detonating. Typically, 1 kilogram of dynamite burns in about 20 microseconds. In this very short time it vaporizes and generates very high pressures and temperatures. The dynamite is usually ignited with a detonator which is a small-size charge of dynamite as well, but enough to ignite the larger charge. The detonator must get a large current through it in order to be set off. For safety reasons, the detonator is designed such that a large current has to be applied. A typical current strength is some 5 Amp.

Explosives can be classified by their chemical composition. Dynamite itself consists of a combination of the explosives glyceroltrinitrate and glycoldinitrate. Since the combination of these two give a fluid, they are mixed with celluloid-nitrate and then give a gelatinous material. Additives of certain (secret) components result in different types of dynamite. Because all of these dynamites contain glyceroltrinitrate, contact with the skin or inhalation, causing head aches, must be avoided.

Since the burning of the dynamite takes place in a very short time generating sudden high pressures and temperatures, it is obvious that in the ground, immediately around the explosive a non-linear zone is created, that means the rock or soil will have undergone some permanent change by the explosion. Three processes are at work there: deformation of the material, conversion of work into heat and geometrical spreading. There will be a distance from the source where there will be no deformation any more; this is given in figure (3.11). The behaviour of the dynamite as a function of time is given in the lower of figure (3.11). In time, we first have an intense shock wave with a complete shattering of the rock or soil. Then, at a certain time, we get two effects, namely a cavity expansion and anelastic rock deformation, until we reach finally a time where we left a cavity which stays there, and an elastic wave originating from this area. So there will always be a cavity left when using dynamite. This cavity is not the same as the radius where the anelastic wave becomes an elastic wave. There has actually been some people who have dug out these cavities in order to see how the cavity changed with a different charge of dynamite. It turned out that the cavity radius was proportional to the cube root of the charge mass.

The dynamite signature

Let us now look at the pressure resulting from a dynamite explosion. It will not be

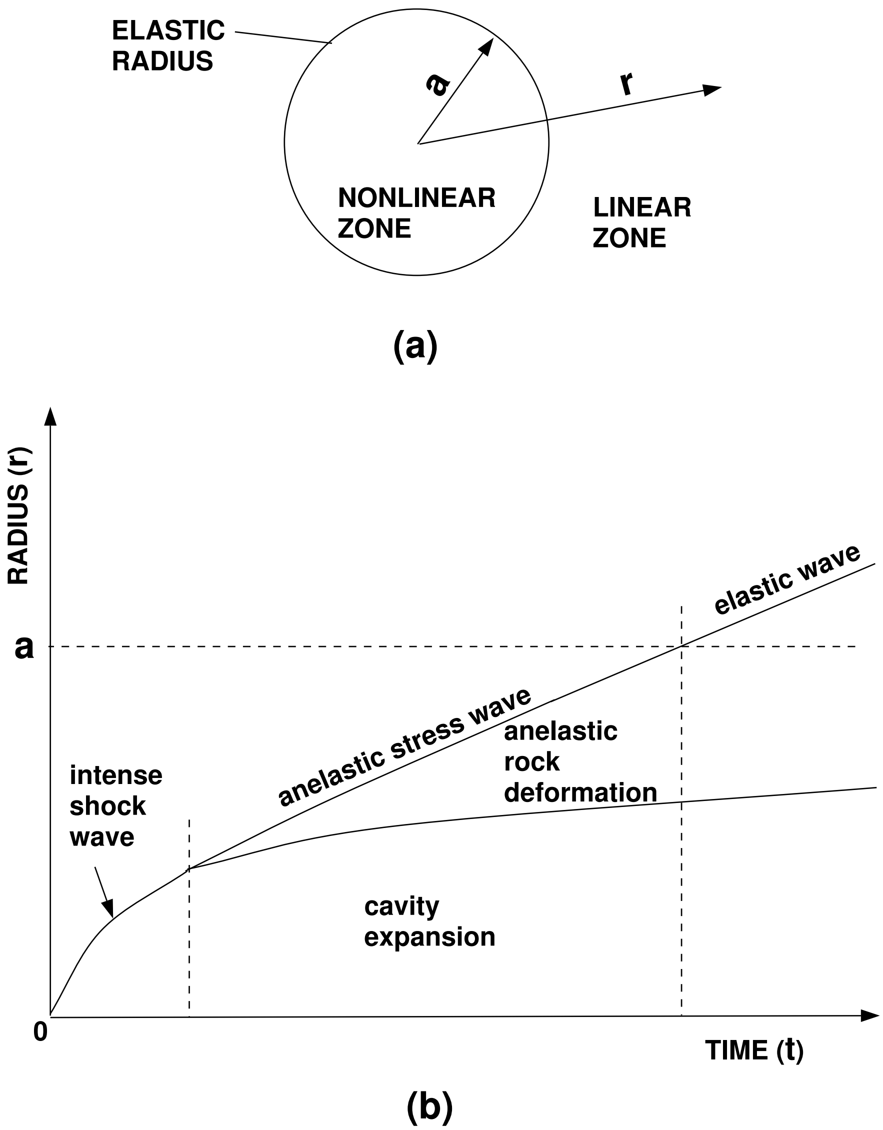

Figure 3.11: The behaviour of dynamite: (a) the characteristic zones in space, and (b) the radius as a function of time with its characteristic zones.

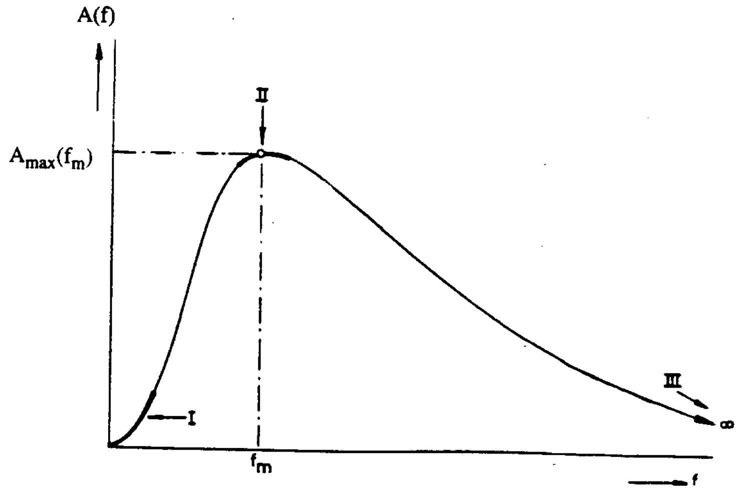

Figure 3.12: Amplitude as function of frequency of dynamite signature (from: Peet, 1964)

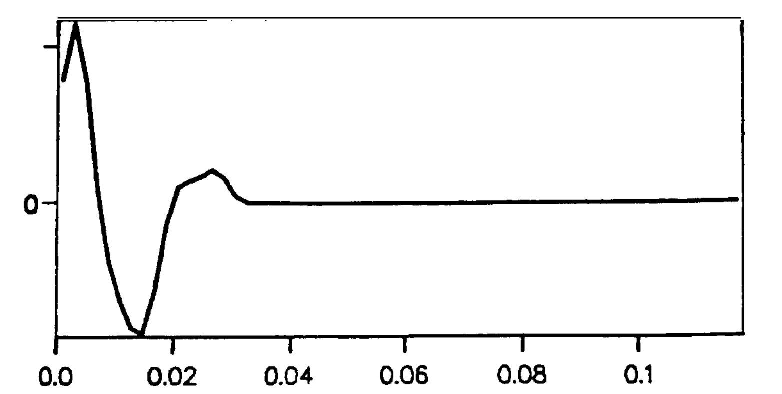

Figure 3.13: Time-domain signal of dynamite, obtained from measurements in the field.

shown how the following results are obtained; that is beyond the scope of these course notes. These results were derived theoretically from shock-wave theory, and are shown in figure Figure 3.12. In this figure we see that the spectrum has a maximum and that is also what is observed in field experiments.

Also, from experiments in the field, the dynamite signature has been determined, although the experiments are not always reliable. The results are shown in Figure (3.13), showing a pulse with a sharp peak at the beginning. The amplitude and phase spectrum are given in Figure (3.14) and Figure (3.15).

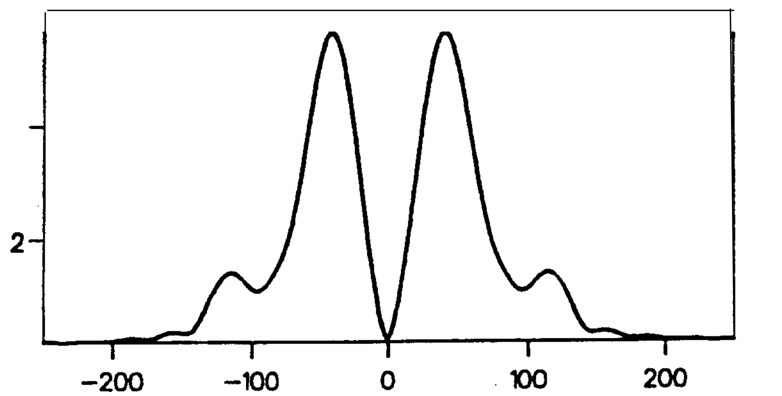

Figure 3.14: Amplitude spectrum of dynamite signature.

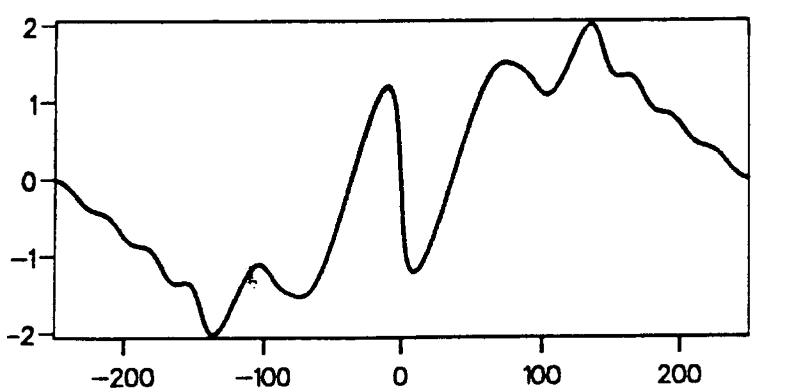

Figure 3.15: Phase spectrum of dynamite signature.

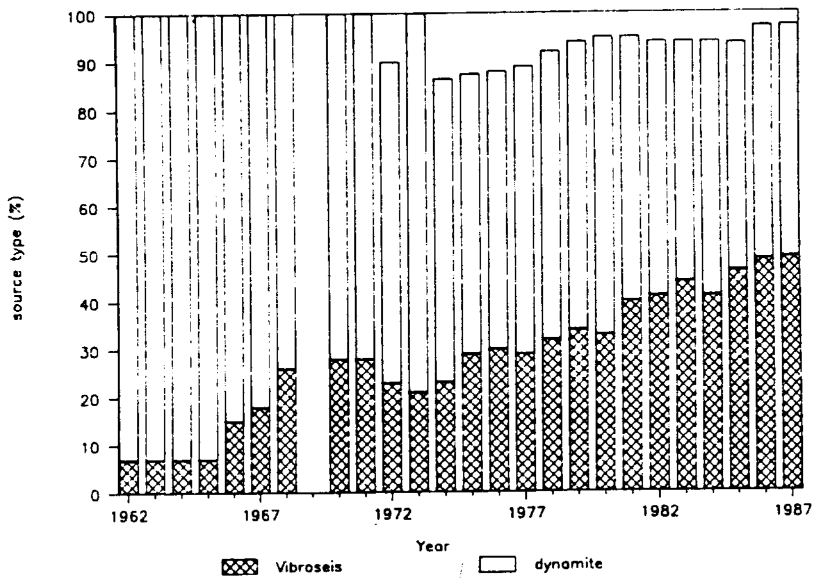

Figure 3.16: The contribution of Vibroseis and dynamite to the total number of crew months spent in land petroleum exploration, in %, for the years 1962-1987.

3.2.4 The advantages and disadvantages of Vibroseis and dynamite

One may wonder why it is not normal practice in seismic exploration to use an impulsive source, since, after all, it is the earth's impulse response we are after. As can be seen in Figure (3.16), the most well-known impulsive seismic source, dynamite, is indeed used very often in land seismic surveys. There are, however, some distinct disadvantages related to the use of an impulsive source like dynamite.

First of all, due to the high energy density of the dynamite explosion, severe harm can be done to the environment. In any case, the destructive nature of the dynamite source prohibits its use in densely populated areas. Second, a hole has to be drilled for every shotpoint in which the dynamite charge is placed. Third, the high energy-density of the explosion results in a non-linear zone surrounding the explosion. Although the ignition time of the dynamite itself is short compared with any time duration of interest in seismic exploration, this nonlinear zone results in a distorted wavelet. The high-frequency content of the signal decreases when the charge size is increased (the low frequency content increases). This yields a trade-off between penetration and resolution: a large charge size has better penetration, but lacks high frequencies. Another disadvantage of the creation of a nonlinear zone around the dynamite explosion is that effectively a wavelet is transmitted into the earth that is not an impulse, and has a shape which is not accurately known and cannot be measured easily.

The Vibroseis source has some distinct advantages over the dynamite source. First, the emitted signal contains an amount of energy that is (roughly) comparable to the energy contained in a dynamite signal. Because of the use of an expanded impulse, the energy density of the source wavelet in the Vibroseis technique is much less than the energy density of the dynamite wavelet. Therefore, destructive effects are much less severe. Secondly, Vibroseis provides us with a direct means to measure and control the outgoing wavelet. Thirdly, there is no need to drill holes when using Vibroseis.

There are, however, also some disadvantages connected with the use of Vibroseis as a source. Firstly, a single vibrator in general does not deliver a sufficient amount of energy required for seismic exploration purposes, so that arrays of vibrators have to be used. Typically, 4 vibrators vibrate at each vibration location simultaneously. Second, as vibrators are surface sources, large amounts of Rayleigh waves are generated. The generation of Rayleigh waves can be suppressed in a dynamite survey by placing the charge at or below the bottom of the weathered layer. In Vibroseis surveys, the Rayleigh waves have a very high amplitude and are an undesired feature on the seismogram. Thirdly, the Vibroseis method can be employed only in areas which are accessible to the seismic vibrator trucks, whose weight may exceed 20 tons. Fourth, correlation noise (i.e. the noise generated by the correlation process that converts the Vibroseis signal into a pulse) limits the ratio between the largest and smallest detectable reflections.

In spite of many disadvantages, the Vibroseis method is now a standard method in the seismic exploration for hydrocarbons. In 1987, Vibroseis was used more often in land seismics than dynamite (the contribution of Vibroseis to the total number of crew months spent in land seismic petroleum exploration was 49 %, whereas the contribution of dynamite was 48.3 %). The operational advantages of the Vibroseis method over the conventional dynamite survey result in an average cost per kilometre of Vibroseis which is only two-thirds of the cost per kilometre for a dynamite survey (figures for 1987). Also, the average number of kilometres that can be covered per crew month is 30 % higher for Vibroseis surveys than it is for dynamite surveys (figures for 1987). This cost-effectiveness and efficiency, together with the increasing importance of signal control in the search for higher resolution of seismic data and the non-destructive character of the method explains the increasing popularity of Vibroseis. In table (3.1) the advantages and the disadvantages of the Vibroseis and dynamite are tabulated.

	Advantages	Disadvantages
Vibroseis	1. Less destructive than dynamite : can operate in urban areas 2. Not labour-intensive : cheap in operation 3. Some control over outgoing signal	1. One truck does not deliver enough energy : arrays, so directivity 2. Surface source : many Rayleigh waves 3. Can only operate in areas which can support 20 tons 4. Correlation imperfect : correlation noise
Dynamite	1. Buried source : much less surface waves generated than Vibroseis 2. Signal close to δ-pulse	1. Destructive : cannot operate in urban areas 2. Labour intensive for making shotholes : expensive in operation

Table 3.1: Advantages and disadvantages of Vibroseis and dynamite

3.3 Seismic detectors

The source generates a mechanical disturbance which propagates in the ground, is reflected, refracted or diffracted, and returns to the surface. When the disturbance propagates in a fluid such as water a temporary variation of pressure is created. Elastic deformation results in movements of the surface and at some point of the surface the acceleration, the velocity or the displacement of a point can be measured. In any case, whether a movement or a variation of pressure is observed, we have to represent it by some other physical quantity which can be easily stored and manipulated. Considering the development of electronic technology, a representation by an electrical voltage is evidently a good solution. The first field component of a seismic data acquisition system is the detector group. The detectors convert the seismic disturbance into a voltage of which the variations represent faithfully the variations of the mechanical disturbance detected, a voltage which is the analog of the seismic disturbance.

The detectors used for seismic exploration work are called geophones since they are used to "hear" echoes from the earth underneath. Sometimes, they are called seismometers but this term is more often applied to long period seismographs used for recording natural earthquakes. The term "detector" applies to all types of seismic-to-electrical transducers. From what has been said before, it will be clear that they can be classified into two main groups: motion-sensitive, mainly for land operations, and pressure-sensitive for operations in water (or fluids), be it for marine seismic work or in the mud column of a borehole, for well-shooting or a VSP. Pressure-sensitive geophones are also called hydrophones.

The types of detectors commonly used in practice, are electromagnetic and piezoelectric transducers and we shall omit all others. Piezoelectric transducers which are pressure-sensitive are used as hydrophones and electromagnetic transducers are used on land. In the moving coil geophone of the electromagnetic type, a voltage is generated by the movement of a conductor in a strong permanent magnetic field. These types are used nowadays.

Geophones are the parts of the system which undergo the roughest treatment. They are planted and picked up many times, they are flung down, run over by the trucks, stamped into the ground by the line men. And yet, they are expected to generate an accurate, noise-free reproduction of the earth movements. They are built to withstand rough handling but a minimum of care on the part of the line men can help in obtaining good quality data.

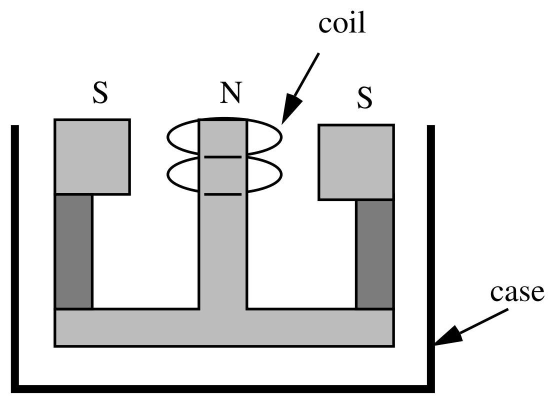

Figure 3.17: Schematic cross-section of a moving-coil geophone.

3.3.1 Geophones

A moving coil geophone (Figure 3.17) operates according to the principle of a microphone or a loudspeaker: the coil consisting of copper wire wound on a thin non-conducting cylinder ("former") moves in the ring-shaped gap of a magnet. Figure 3.17 is the cross section of a cylindrical structure. The annular magnet and polar pieces N and S in soft iron create a radial field in the gap. The only movement allowed for the coil, suspended from springs not shown in the picture, is a translation along the direction of the axis and in the gap. As the coil moves, its windings cut magnetic lines of force and an electromotive force is generated. The output voltage is proportional to the rate at which the coil cuts the lines of magnetic force, that is to say, proportional to the velocity at which it moves. Therefore this type of detector is known as "velocity geophone".

The main parts of the geophone are:

- the moving mass, made up by the coil and the "former" on which it is wound;
- the coil suspension, usually two flat springs, one at the top and one at the bottom, to avoid lateral displacement of the coil;
- the case, with the magnet and polar pieces inside a cylindrical container which protects the other elements against dust and humidity.

The case is placed on the ground and is supposed to follow the ground movement exactly (Figure 3.18). The output voltage is proportional to the velocity of the mass relative to the case and what we are interested in is this relative movement as a function of the movement of the case.

A complete description of geophones must take into account many phenomena beyond the scope of these lecture notes. The final design of a geophone is usually a compromise

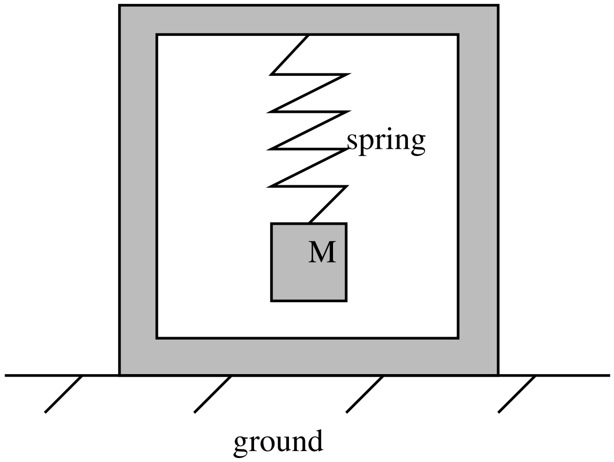

Figure 3.18: The geophone on the ground.

between conflicting requirements. For a geophysicist it is often sufficient to know the basic operating principle of the geophone in order to understand the behaviour of this component as part of the whole data acquisition network. Consequently, the considerations which follow are restricted to the response of an ideal geophone.

Assuming the vertical component of the velocity is:

$$v_z = \frac{dz}{dt}, \tag{3.6}$$

and the output voltage is given by V, the conversion of the motion to the electric signal takes place via the transfer function:

$$R(\omega) = \frac{\text{Voltage}}{\text{Particle Velocity}} = \frac{V(\omega)}{v_z(\omega)} = \frac{\omega^2 K}{\omega^2 - 2ih\omega\omega_0 - \omega_0^2} \tag{3.7}$$

where ω_0 is the resonance frequency of the spring, and K and h are some constants depending on mechanical and electrical components; K represents a sensitivity (proportionality constant) and h a damping factor. Consider now three situations:

$$\begin{aligned}
\omega \to 0: &\qquad R(\omega) \to -\frac{\omega^2}{\omega_0^2}K = \frac{\omega^2}{\omega_0^2}K\exp(\pi i) \\
\omega = \omega_0: &\qquad R(\omega) \to \frac{K}{-2ih} = \frac{K}{2h}\exp(\pi i/2) \\
\omega \to \infty: &\qquad R(\omega) \to K
\end{aligned} \tag{3.8}$$

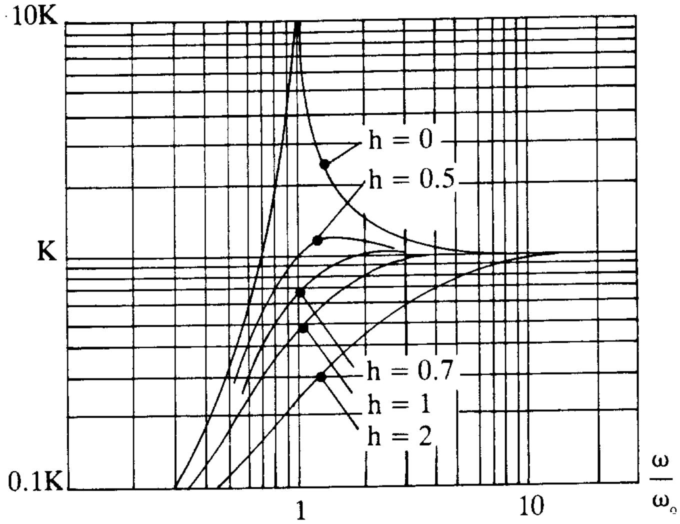

Figure 3.19: Amplitude response of geophone at constant velocity drive (From: Pieuchot, 1984)

These are depicted in Figure 3.19 and Figure 3.20. The received voltage is proportional to the velocity of the ground only at frequencies well above the resonance frequency of the geophone. At these frequencies the constant K is the sensitivity of the geophone, with units of, for example, volts/mm/s.

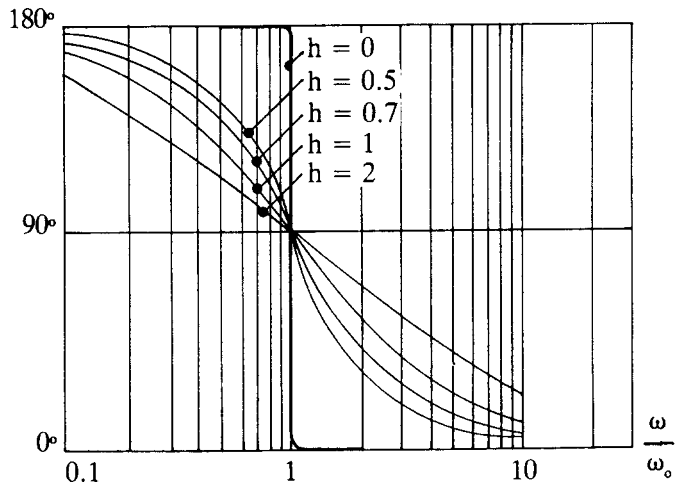

Figure 3.20: Phase response of geophone at constant velocity drive (From: Pieuchot, 1984)

3.3.2 Hydrophones

As has been shown in the foregoing section, the geophone exhibits a flat pass-band characteristic from a few Hertz above the resonance frequency to the spurious frequency. In that pass-band the output voltage V_{Geop} is proportional to the particle velocity v:

$$V_{Geop} = constant \cdot v_z \tag{3.9}$$

We will show in the next paragraph that in the pass band of the hydrophone, the output voltage V_{Hydr} is proportional to the acoustic pressure p, i.e.,:

$$V_{Hydr} = constant \cdot p \tag{3.10}$$

Hydrophones are thus pressure-sensitive detectors and they are used for operations in water-covered areas.

At present often hydrophones with ceramic pressure sensitive elements are used. They operate on the principle of piezoelectricity. A piezoelectric material is one which produces an electrical potential when it is submitted to a physical deformation. The phenomenon is observable in some crystalline structures such as quartz and tourmaline and is used in record player pick-ups. It can also be produced by in artificially-made poly-crystalline ceramics after they have been submitted to a high-intensity electric field (several tens of thousands volts per centimeter). The most commonly used material in seismic applications, is lead zirconate titanate (PZT).

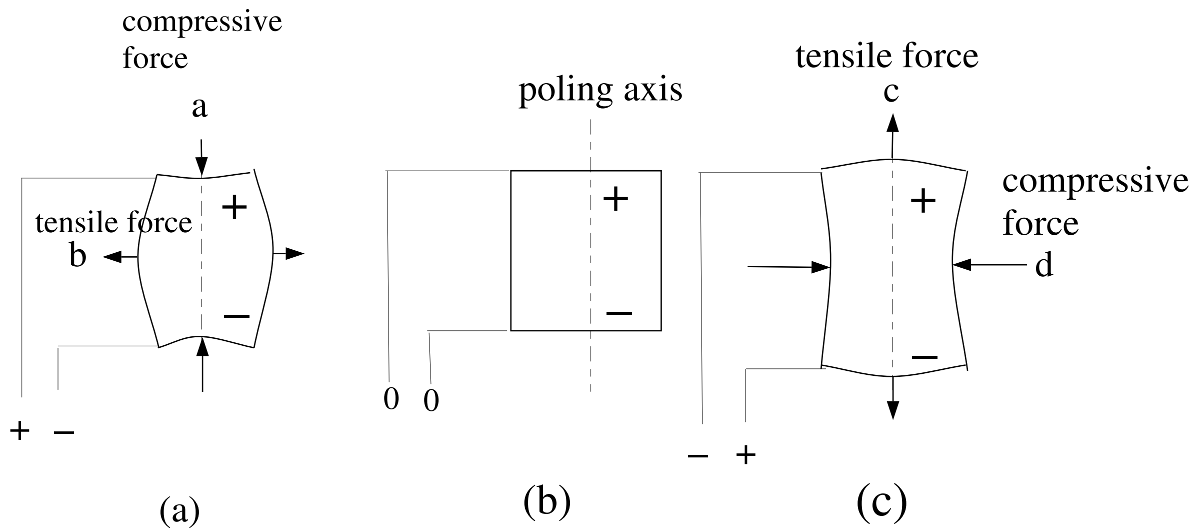

Figure 3.21: Piezoelectric voltages from applied force. (a) Output voltage of same polarity as poled element; (b) output voltage of opposite polarity as poled element.

When compressive and tensile forces are applied to the ceramic element, it generates a voltage. Refer to Figure 3.21. A voltage with the same polarity as the poling voltage results from a compressive force (a) applied parallel to the poling axis, or from a tensile force (b) applied perpendicular to the poling axis. A voltage with the opposite polarity results from a tensile force (c) applied parallel to the poling axis, or from a compressive force (d) applied perpendicular to the poling axis. The magnitude of piezoelectric forces, actions, and voltage is relatively small. For example, the maximum relative dimensional changes of a single element are in the order of 10^{-8}. Amplification is often required and accomplished by other components in the system, such as electronic circuits. In some cases, the design of the ceramic element itself provides the required mechanical amplification. The use of ceramic elements as seismic (pressure) detectors / hydrophones is based on these principles.

Figure 3.22 represents the cross section of a typical piezo-electric hydrophone. It consists of a plate of the piezo-electric ceramic placed on an elastic electrode. The active element is deformed by pressure variations in the surrounding water and it produces a voltage collected between the electrode and a terminal bonded to the other face. The electrode rests on a metallic base which supports its ends and also limits the maximum deformation so as to avoid breaking the ceramic, even if the hydrophone is accidentally submitted to high pressures (when the streamer is broken and drops to the bottom for instance).

With its mass, the active element produces a voltage not only under a variation of pressure but also when it is subjected to acceleration. In offshore operations, with the

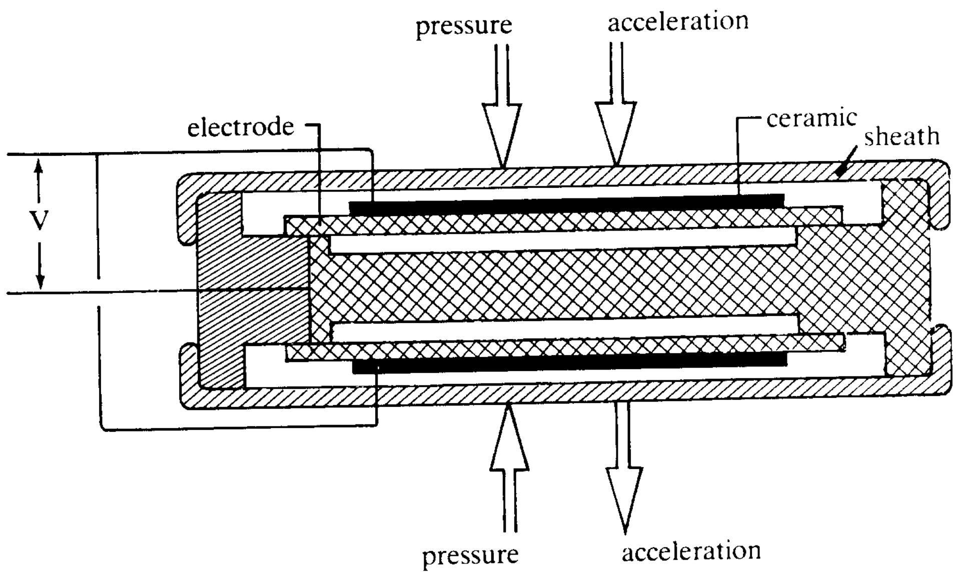

Figure 3.22: Schematic cross-section of a piezoelectric hydrophone (From: Pieuchot, 1984)

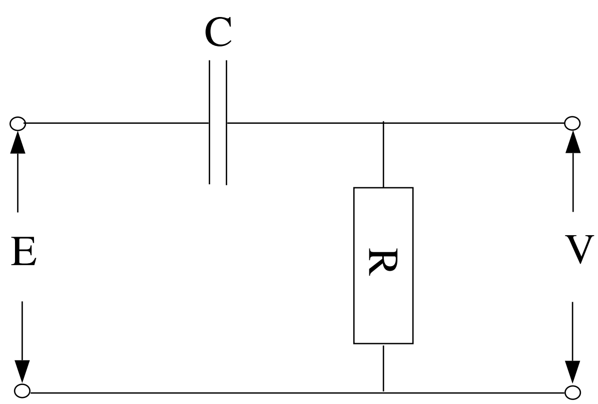

Figure 3.23: Simplified circuit for deriving the hydrophone response.

boat movements and the waves, the hydrophones are continually subjected to accelerations and this would create a high level of noise in the absence of any compensation. The protection against acceleration is obtained by assembling two elements as shown in the figure. The voltage produced by an acceleration cancel each other whereas those produced by a pressure wave add.

As with the geophones in land operations, the hydrophones are always assembled in multiple arrays at each trace. They are often assembled so as to increase the capacitance (more hydrophones in parallel than in series) and decrease the low-frequency cut-off. The network model for the hydrophone is given in Figure 3.23.

V/E is the transfer function since E represents the variations of pressure in the water. From the circuit given in Figure 3.23, the transfer function $R(\omega)$ can be derived:

$$R(\omega) = \frac{\text{Voltage}}{\text{Pressure}} = \frac{V}{E} = \frac{R}{R + \frac{1}{i\omega C}} = \frac{i\omega CR}{1 + i\omega CR} \tag{3.11}$$

Consider now three situations:

$$\begin{aligned}
\omega \to 0: \qquad & \frac{V(\omega)}{E} \to i\omega CR = \omega CR \exp(\pi i/2) \\
\omega = 1/CR: \qquad & \frac{V(\omega)}{E} \to \frac{i}{1+i} = \frac{1}{2}\sqrt{2}\exp(\pi i/4) \\
\omega \to \infty: \qquad & \frac{V(\omega)}{E} \to 1
\end{aligned} \tag{3.12}$$

The amplitude and phase response are given in Figure 3.24.

It is now interesting to compare this response to the one from the geophone. At low frequencies the responses are out of phase by $\pi/2$, decreasing to $\pi/4$ at higher frequencies and in phase at high frequencies. This can be important when comparing two seismic sections, one shot on land and the other one shot at sea.

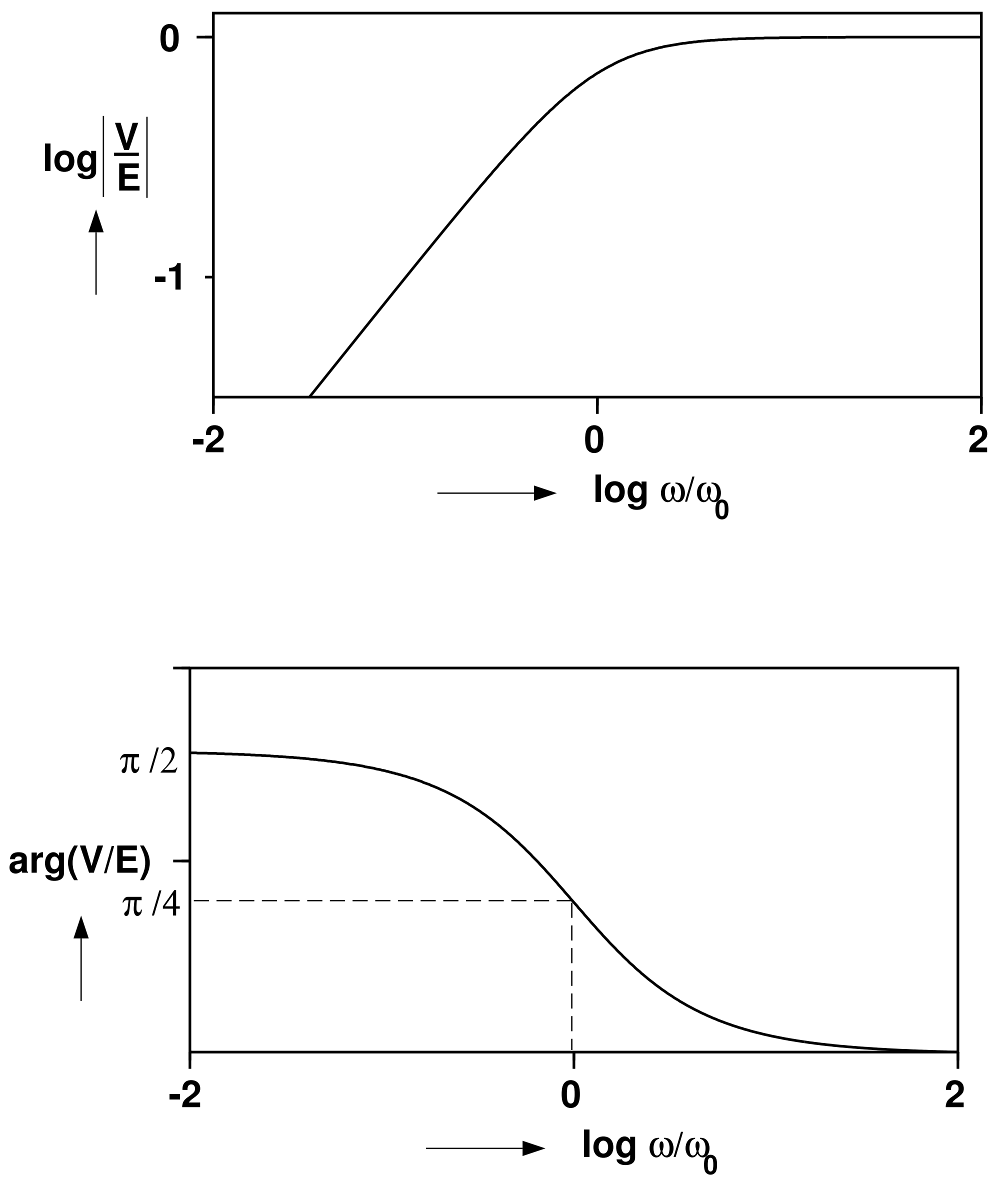

Figure 3.24: Amplitude and phase response of a hydrophone.

3.4 Seismic recording systems

The modern seismic data recording system is a compound of electric subsystems (amplifiers, filters, etc.). The (glasfibre) cable system may often be considered integral part of it. It has as input analog electrical signals from the seismic detectors (see section on geophones and hydrophones) and puts digital data out on magnetic tape. Nearly all systems offer the facility of instant data verification through the creation of output on paper record, the so-called "monitor recording".

In a very general sense, a recorder consists of several parts, namely amplifiers, filters and an A/D converter, before it is stored on (magnetic) tape. The analog signal comes from the geophones into the system, where it is first amplified. The data can be filtered, the most important one being the anti-alias (high-cut) filter. Then the data is converted to a digital signal using the A/D converter, giving digital data which can be stored on disc or computer tape.

3.4.1 (Analog) filters

An important setting of a data recording system is that of different filters. The filters are analog filters. Some of these filters may be predetermined but others must be left at the discretion of the user and must be adjustable in the field. These filters can be categorised into two groups, namely passive and active filters. Passive filters are built from passive electrical elements: resistors, capacitors and coils. Active filters have an amplifier as an integral part of the filter. Usually there are three types of filters available to the user in the field: low-pass (high-cut), notch and high-pass (low-cut) filters.

In the following the principles of passive filters will be dealt with. Let us look at a general scheme of a filter by considering figure (3.25). When a potential difference E is put over a series connection of two passive elements with impedances Y and Z, and when we measure the potential difference V over the Y component, the ratio of the two potentials is given by:

$$\frac{V}{E} = \frac{Y}{Z+Y} \tag{3.13}$$

The components Y and Z can be any components as tabulated in appendix C.

For a resistance, the impedance is R, for an inductance $i\omega L$, and for a capacitance $1/i\omega C$. So, when the component Y is an capacitance and Z a resistance, the measured potential difference is a "high-cut" (or "low-pass") version of the input voltage E. This can be seen by substituting the values in the above equation:

$$\frac{V}{E} = \frac{\frac{1}{i\omega C}}{\frac{1}{i\omega C} + R} = \frac{1}{1 + i\omega CR} \tag{3.14}$$

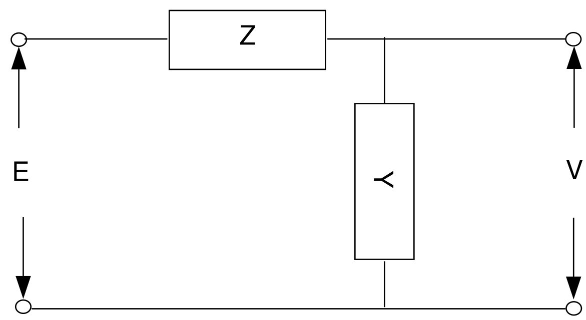

Figure 3.25: A passive filter.

which is a ratio, dependent on the frequency ω. When we write this in polar coordinates, we get:

$$\frac{V}{E} = \frac{1}{1+i\omega CR}\frac{1-i\omega CR}{1-i\omega CR} = \frac{1}{1+\omega^2C^2R^2} + i\frac{-\omega CR}{1+\omega^2C^2R^2} = \frac{1}{(1+\omega^2C^2R^2)^{1/2}}\exp(i\phi) \quad (3.15)$$

where ϕ is the phase angle. When ω is small, then ωCR can be neglected compared to 1 in the amplitude factor and thus, V/E behaves like 1 (amplitudewise). When ω is large then 1 can be neglected compared to ωCR, and the numerator approaches ωCR so V/E will behave like $1/\omega$. This is thus a high-cut filter.

In the same way we can derive that when Y is a resistor, the filter acts as a low-cut or high-pass filter. It is customary to specify a filter by its so-called corner frequency, i.e., the frequency where $\omega LCR = 1$. With a high-cut filter as above, the signal will be significantly damped above this frequency, with a low-cut filter the signal will be significantly damped below this frequency. The foregoing filter was an example of a passive filter, i.e., a filter built-up of passive elements (R, L, C).

Why do we need these filters in our geophysical measurements? Let us discuss them separately, first the low-cut filter. As the name says, low-frequency waves can be suppressed with these filters. On land, filtering is sometimes applied to suppress the surface waves or ground roll, although there is a preference for keeping surface waves in the seismogram and remove them later during processing. At sea, a low-cut filter is needed to suppress the waves at the surface of the sea itself.

A most important filter is the anti-alias filter, needed for proper sampling in time of the seismic signal. Aliasing of the seismic signal should be avoided when we sample it in time. This means that the highest frequency in the signal should at least be sampled with 2 samples per full period. But we do not know the frequency content of our signal beforehand and therefore we make sure, using a high-cut filter, that above a certain frequency, the

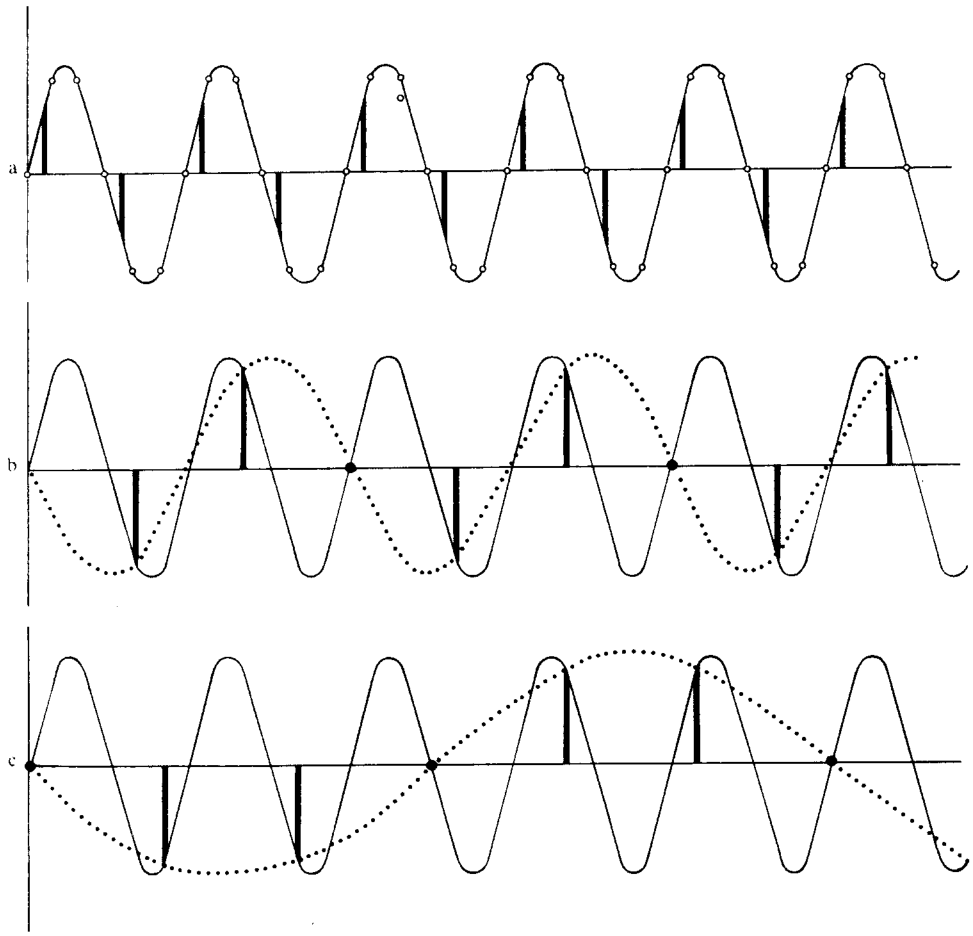

Figure 3.26: The time-domain aspect of aliasing.

signal is suppressed below a certain level. The high-cut filter must reduce the signal above the Nyquist frequency below the noise level. The Nyquist frequency is given by: $f_N = 1/2\Delta t$. The effect of aliasing in the time domain is illustrated in figure (3.26). Once the frequency content of the signal is suppressed sufficiently above the Nyquist frequency, digitizing the data makes real sense. Because of this application, this filter is also called an anti-alias filter or just alias filter. This filter must always be set according to the sampling rate.

Another type of filter which is usually present in a seismic recording system, is the notch filter. Once in a while, it can happen that 50 or 60 Hz interference from power cables is disturbing the seismic measurement (Europe 50 Hz, America 60 Hz). When input balancing circuits, cable screening fails to cure this problem, it is possible to use an active steep-flank so-called "notch filter" to cut the signal at these frequencies. It should be noted however that by cutting the signal before recording, we may also cut valuable information from our data and we may never be able to retrieve it later on.

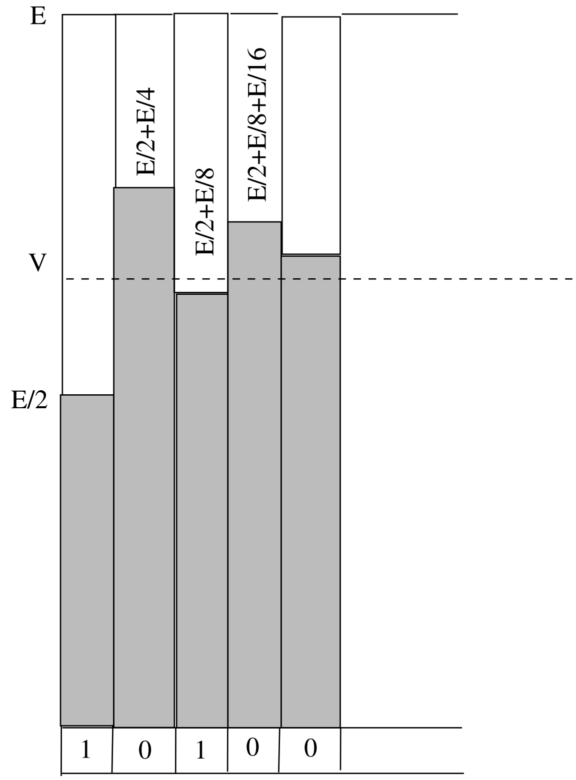

Figure 3.27: Conversion by successive approximations.

3.4.2 The Analog-to-Digital (A/D) converter

In this part the analog-to-digital conversion is discussed. The input is a continuous signal voltage, while the output is a sequence of bits. There are several ways of converting an analog signal to a digital one; we shall only discuss the one called the converter by successive approximations. This type of converter starts to compare the voltage from the side where the signal is largest so which will result in the first bit being the "most-significant" bit. Let us consider figure (3.27). First the voltage is compared to a reference voltage E, divided by 2. If the voltage is larger, then the first bit will be set to 1, otherwise to zero. In the second stage, an amount of E/4 is added to or subtracted from the earlier amount of E/2, and again the comparison is made with the signal. If the signal is again larger, a bit value of one will added to the earlier one, otherwise a zero. And so we go on with adding or subtracting E/8, and so on, and so on, until we have reached the maximum amount of bits. An A/D converter is usually given by the amount of bits, e.g. a 16-bits converter. We can see that we make an error when we digitise the data; the error will be half the so-called least-significant bit (LSB).

The amount of bits resulting from a seismic survey is usually quite enormous, especially in 3-D seismics. A simple example: assume we have 4000 channels, and we record data for 6 seconds with a sampling rate of 2 ms; the value of the sample is given by 24 bits.

Then the total amount of samples per shot would be : 4000 x 6 x 500 x 24 = $288 \cdot 10^6$ bits = 288 Megabits per record (shot). This is quite an amount of data, realizing that this is recorded for each shot and offshore, where shots are fired roughly every 10 seconds, thousands of shots are fired.

3.5 Total responses of instrumentation

In the beginning of this chapter, we defined a general model that was assumed behind the whole seismic system, namely a convolution of the different responses, i.e.,

$$X(t) = S(t) * G(t) * R(t) * A(t) \tag{3.16}$$

where the responses were defined in the introduction (eq. (3.1)). A convolution in time is equivalent to a multiplication in the Fourier domain, see the chapter on Fourier analysis. Therefore the seismogram can be written in terms of frequencies as:

$$X(\omega) = S(\omega)G(\omega)R(\omega)A(\omega) \tag{3.17}$$

We see that the seismogram consists of (complex) multiplications of the individual transfer functions. Since the multiplications are complex, it can be written as a multiplication of amplitudes and adding of phases, i.e,:

$$\begin{aligned} X(\omega) &= |S(\omega)||G(\omega)||R(\omega)||A(\omega)| \exp(i\phi_S)\exp(i\phi_G)\exp(i\phi_R)\exp(i\phi_A) \\ &= |S(\omega)||G(\omega)||R(\omega)||A(\omega)| \exp\{i(\phi_S + \phi_G + \phi_R + \phi_A)\} \end{aligned} \tag{3.18}$$

where the symbols ϕ_i denote the phase of the component i. In figure 3.28, we have given an example of such a system. In the figure we have taken the example of a recording that is made with dynamite, detected with a geophone and recorded with a certain sampling interval (with then the Nyquist frequency following as $1/2\Delta t$). From this example, we can see that the source is mostly determining the total response. The geophone mostly affects the low frequencies.

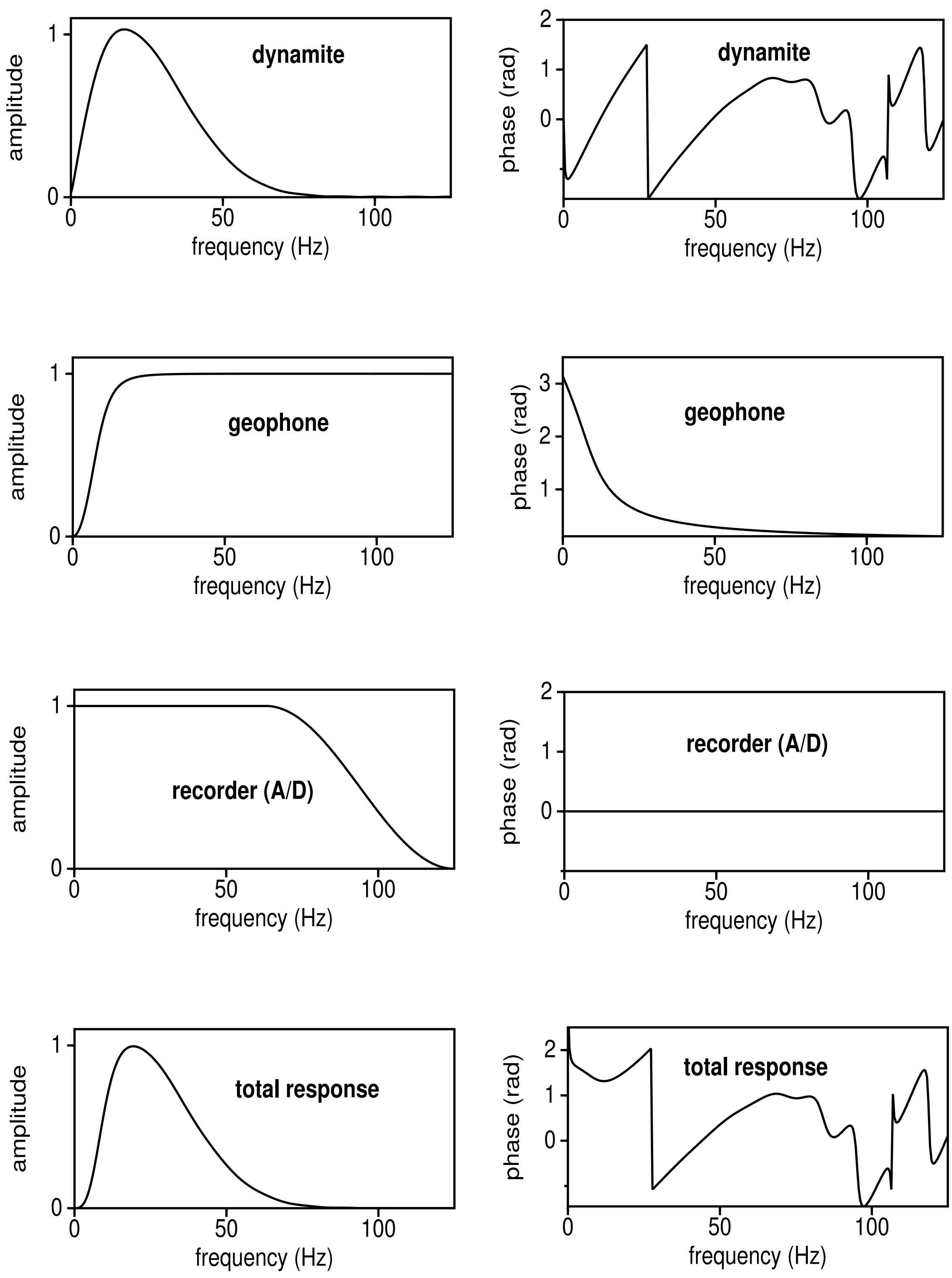

Figure 3.28: The responses due to dynamite source (upper figure), received by geophone of 10 Hz (next two figures), recorded with sampling interval Δt=4 ms (next two figures), resulting in total response (bottom). Note that amplitudes multiply and phases add.