

## GEOPHONE SPURIOUS FREQUENCY: WHAT IS IT AND HOW DOES IT AFFECT SEISMIC DATA QUALITY?

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### ABSTRACT

The Spurious Frequency of a geophone is normally specified by manufacturers but is less frequently understood by users. The Natural Frequency is well understood as the resonant frequency of the spring mass system in the working axis of the geophone. All discontinuities in the transfer function of the geophone above the natural frequency are termed spurious resonances. 24 bit technology and digital filtering have pushed the anti-alias (or high-cut) frequencies of modern recording systems to greater than 4/5 Nyquist, extending the available recording bandwidth, however also getting closer to the spurious danger zone. We can now no longer ignore the spurious frequencies of the geophones with which we record such broadband data. Through this paper we will explain this often overlooked geophone parameter by discussing the mechanism within the geophone element that produces the resonance, how we measure that resonance and the effect it can have on seismic data through examples from some field tests.

### SPURIOUS FREQUENCY: WHAT IS IT?

Geophones are designed to respond to extremely small ground displacements. A particle velocity of 0.1 mm/s, which generates an amplitude of 3 mV in a geophone is caused by a displacement of the ground of only 160 nanometres at 100 Hz, the displacement is even smaller at higher frequencies. It is therefore understandable why any additional mechanical micro-movement within the geophone will easily result in voltage signals comparable to those produced by these extremely small ground displacements.

Traditionally the springs used in geophones are flat membrane discs with spring arms linked to concentric rings. They are designed to move linearly in their working axis but by nature are also free to move perpendicular to this axis (Fig. 1). This lateral movement is kept as small as possible but is essential to allow freedom of movement of the geophone coil in the main axis. The spring mass resonance of the geophone in its working axis is called the natural frequency. The spurious frequency is the resonance of the system perpendicular to this normal working axis and is a combination of multiple modes of movement. Ground motion in this plane, either transverse or rotational, may cause the geophone to resonate at the spurious frequency, which is taken

as the lowest of these resonance modes. The spring is designed to have high stiffness in the direction perpendicular to its working axis, hence the high frequency nature of the spurious resonance. The coil motion in this plane is virtually undamped by the coil form. The eddy current damping is small because of the limited variation of magnetic flux within the coil when it is moved in the plane of the radial magnetic field. However due to the construction of the spring arms and the constant movement of the coil in the working axis a part of the cross axis motion is translated into a movement in the main axis. Although this in-axis movement is properly damped, the cross-axis driving force is not and once set up the resonance will "ring" on for a significant time. These effects apply to all geophones irrespective of whether they are designed for vertical, horizontal or other orientations.

Spurious frequency is an important parameter as it effectively sets the upper limit of the usable recording bandwidth of a specific type of geophone (Fig. 2). At this resonance, as at the natural frequency there is a change of phase in the geophone output and a strong variation in sensitivity. However the variation in phase and amplitude are complex and difficult to model due to the multiple modes of resonance.

Spurious frequency manifests itself in seismic data as strong ringing noise running through the record. The large amplitude first arrivals in seismic data may set up the spurious resonance. As spurious frequency is easily started by transverse or rotational motion of a vertical geophone it is often seen after the onset of ground roll, the elliptical particle motion characterizing ground roll very easily excites the spurious frequency in geophones. Figure 3 shows an example section contaminated with spurious frequency at about 180 Hz. In this instance there was a mismatch between the spurious frequency of the geophones (typically 180 Hz) and the anti-alias filter in the recording system which had been set for 1 ms sampling (high-cut 250 Hz with a 72 dB/octave ramp).

Normally we choose a geophone with a spurious frequency above the anti-alias frequency of the recording system, the strong high cut filters being adequate to attenuate the signal induced by the mechanical resonance in the geophone element. In the past this selection has been quite

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# Spurious of a modern geophone

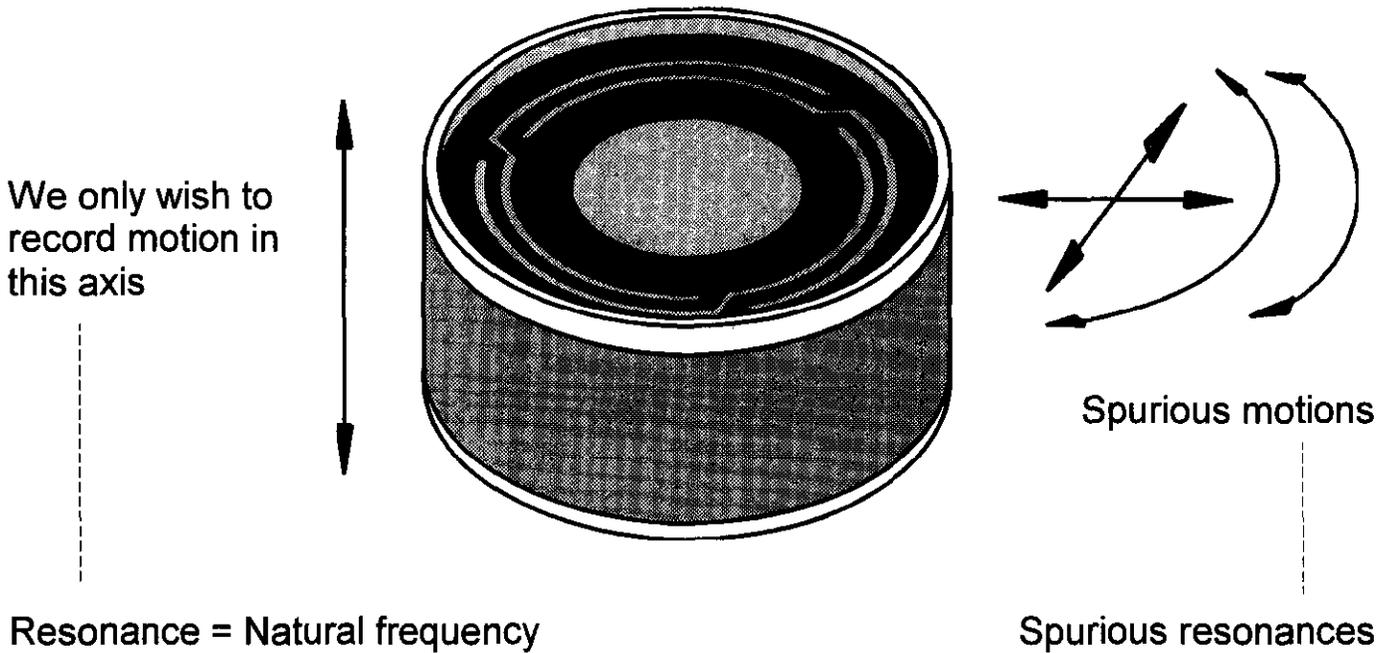


Fig. 1. Schematic diagram of a modern geophone showing the motions that created spurious frequencies.

# Geophone transfer function

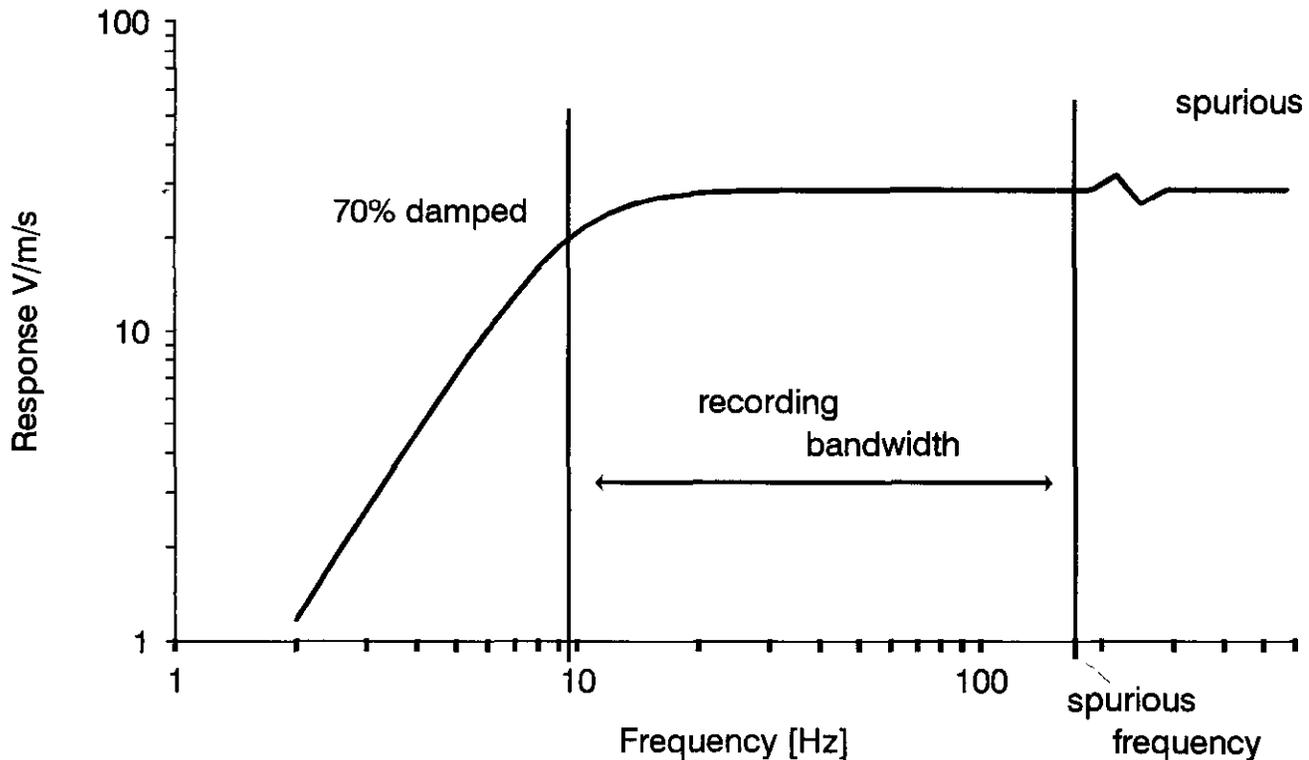


Fig. 2. Geophone transfer function showing the recording and spurious frequency band.

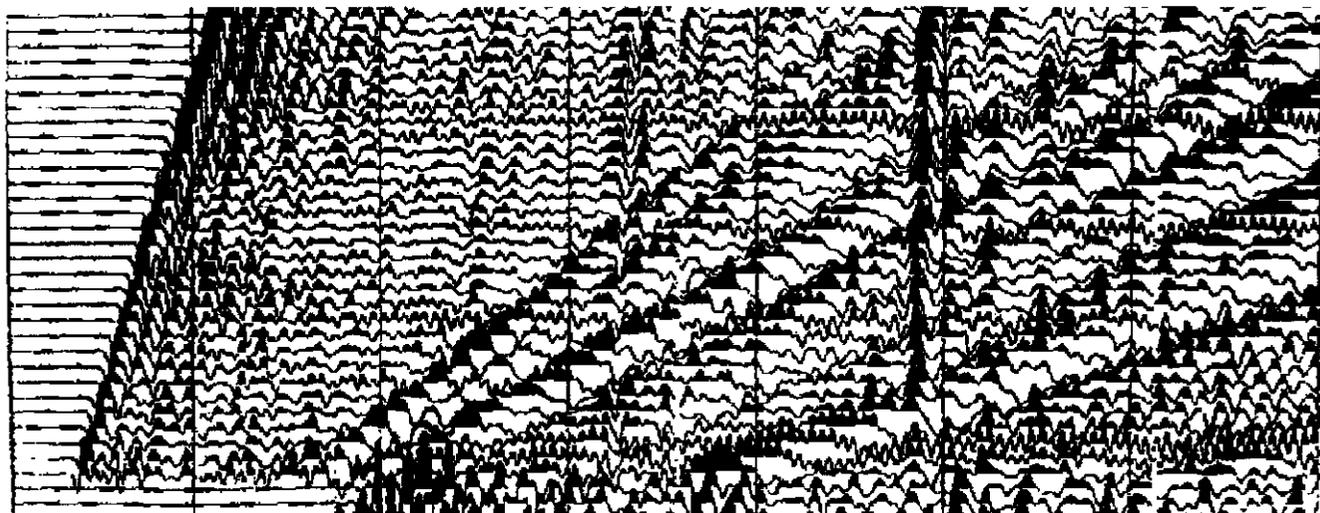


Fig. 3. An example of a seismic section contaminated by spurious frequencies.

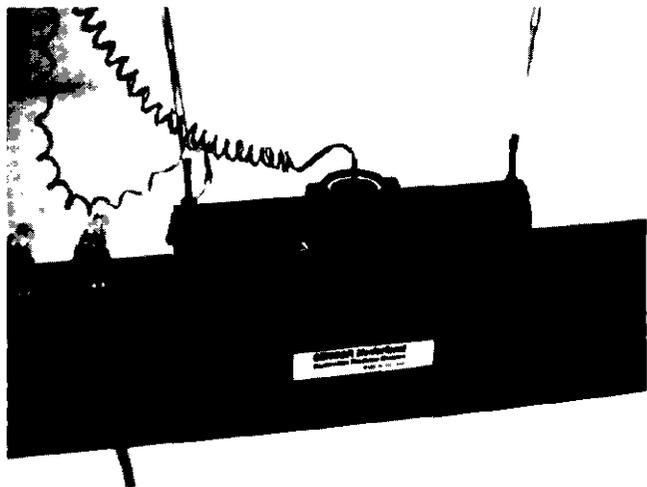


Fig. 4. Experimental apparatus to create motions that generate spurious frequencies.

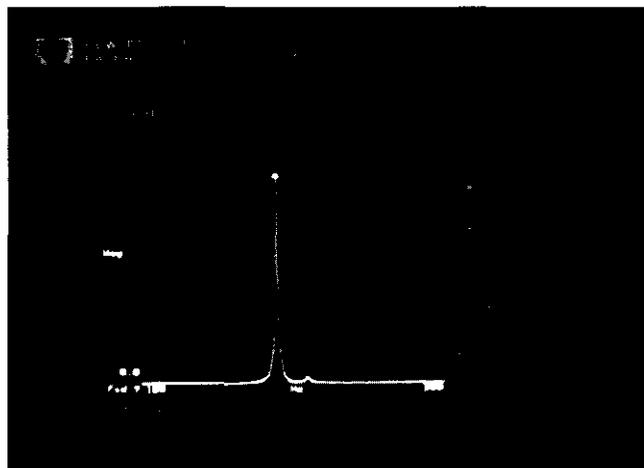


Fig. 5. Spectrum analyzer output shows the spurious peak.

straightforward as many geophones were designed for systems operating to 1/2 or 2/3 Nyquist. At 2 ms sampling this relates to an anti-alias frequency of 125 Hz to 167 Hz. However care must be taken if these geophones are used with a higher sample rate and more subtly with systems with 4/5 Nyquist anti-alias filters as would be found in modern 24 bit recording systems, where the filter starts rolling off at over 200 Hz.

The direct relationship between the natural and the spurious frequencies lies within the geophone spring design. The basic mass spring system can be separated into a vertical and horizontal system. Mass (moving coil) and spring material constants are equal in both systems, the specific design dictating the relation between the resonance frequencies. The ratio of the vertical vs. horizontal stiffness parameter ( $k$ ) is usually a compromise between that desired and that which is

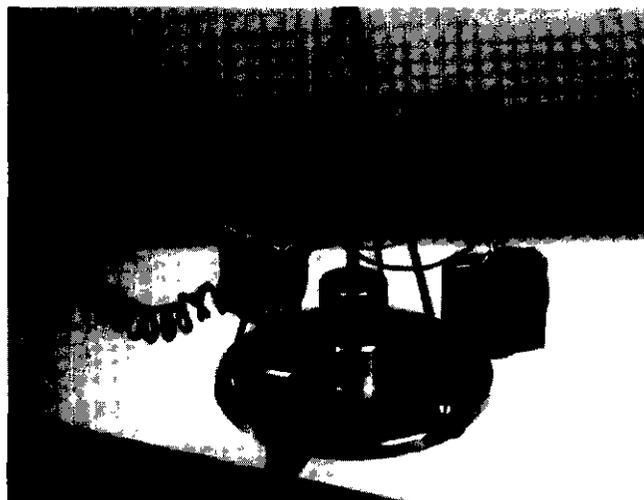


Fig. 6. Photograph of a GeoPinger.

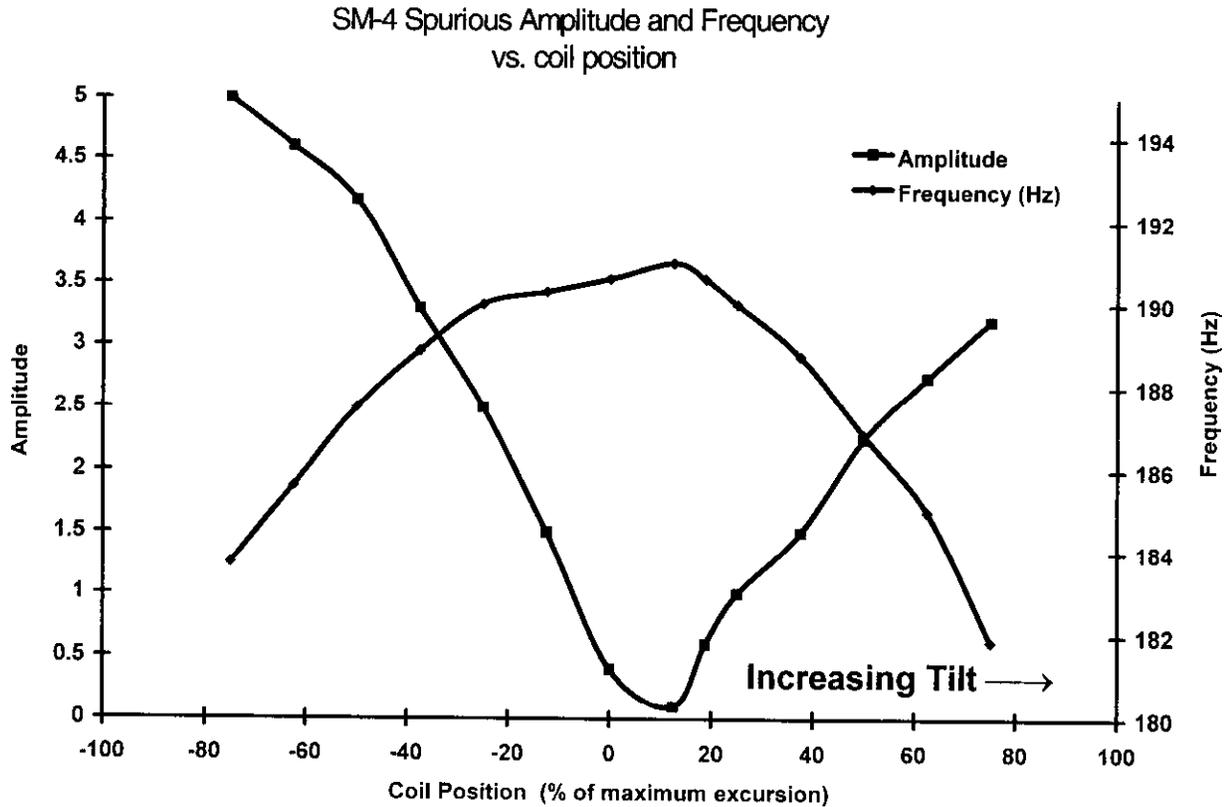


Fig. 7. Graph of geophone amplitude and frequency response as a function of coil position.

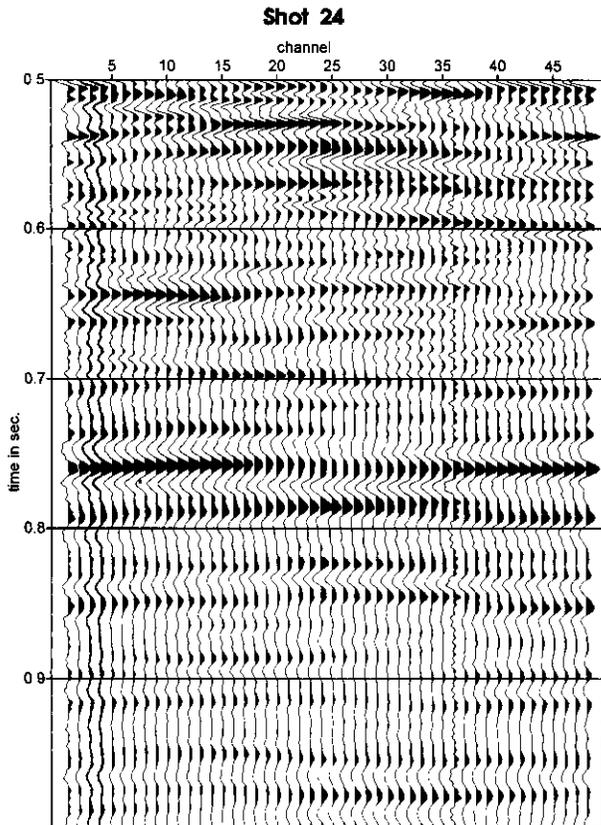


Fig. 8. Data from field test #1 showing the contamination on channel 36.

mechanical feasibility. We have been able to use higher spurious frequency geophones for quite some time but normally this has meant some compromise: higher natural frequency; higher distortion or a less robust design; more prone to damage, reducing field life. These are all direct consequences of stiffening the spring to push the spurious resonance to higher frequencies. The stiffer springs place more stress on the spring arms when they are flexed in their flat plane. Often a micro-shock damper system must be designed within the spring to absorb impact and relieve these stresses to build back some resilience.

Through careful spring design and the use of finite element modeling techniques for stress and force analysis it is now possible to manufacture geophones with a spurious frequency well above 200 Hz, that maintain field reliability and retain the tight tolerances and low distortion demanded to match 24 bit systems.

One limitation is that inconsistencies in materials and manufacturing process have a large effect on the "stability" of the spurious frequency. With relatively low spurious frequencies (< 200 Hz) this is a lesser problem than with the extended spurious frequency geophones. Due to this inconsistency spurious frequency is often specified as "greater than..." indicating that, when measured, one will find a band in which the resonances will occur.

Very strict manufacturing processes, design procedures and correct specification, will ensure that geophones could

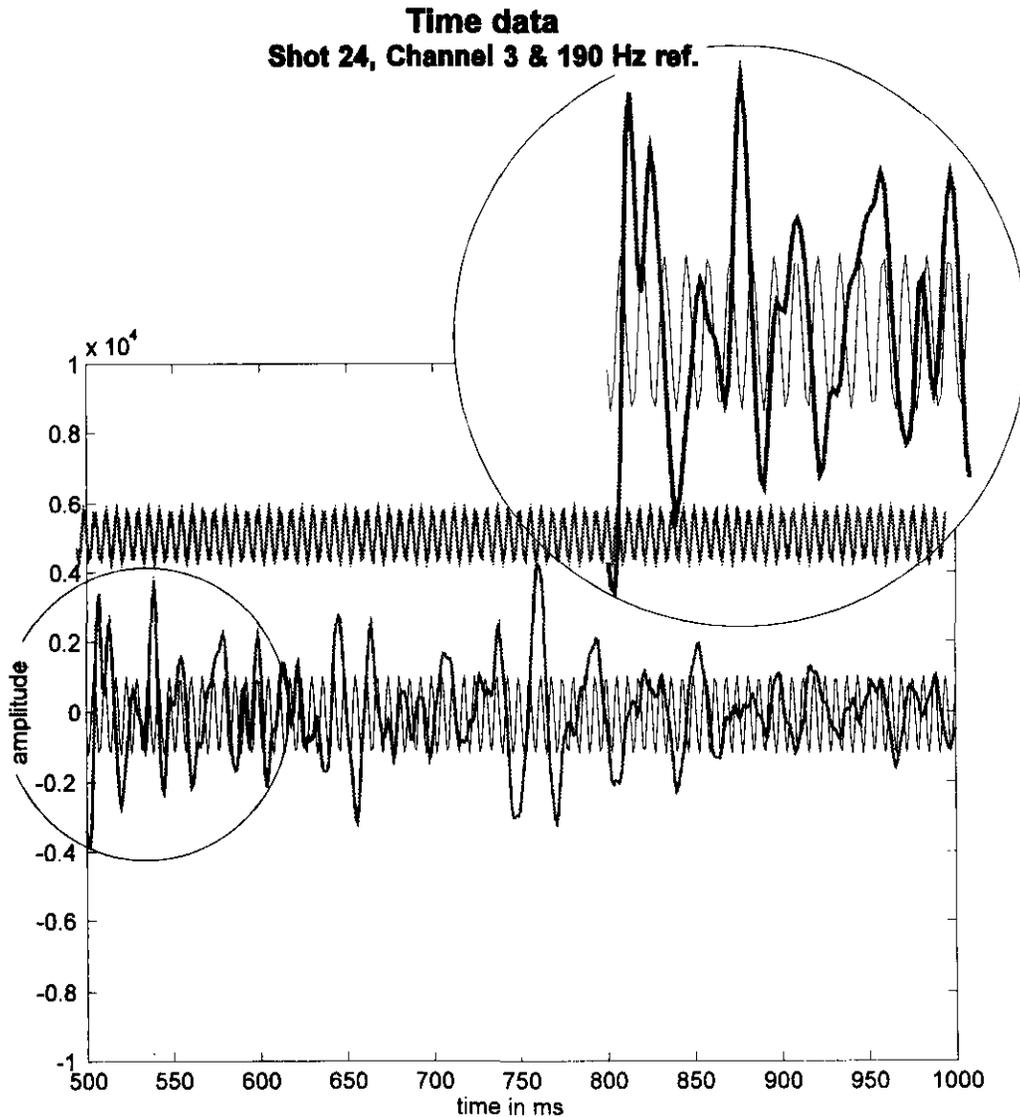


Fig. 9. Channels 3 from shot 24 (Fig. 5) superimposed on a 190 Hz reference frequency.

never appear in a seismic survey that drop below this expected bandwidth and contaminate costly data.

#### MEASURING SPURIOUS FREQUENCY IN THE LABORATORY

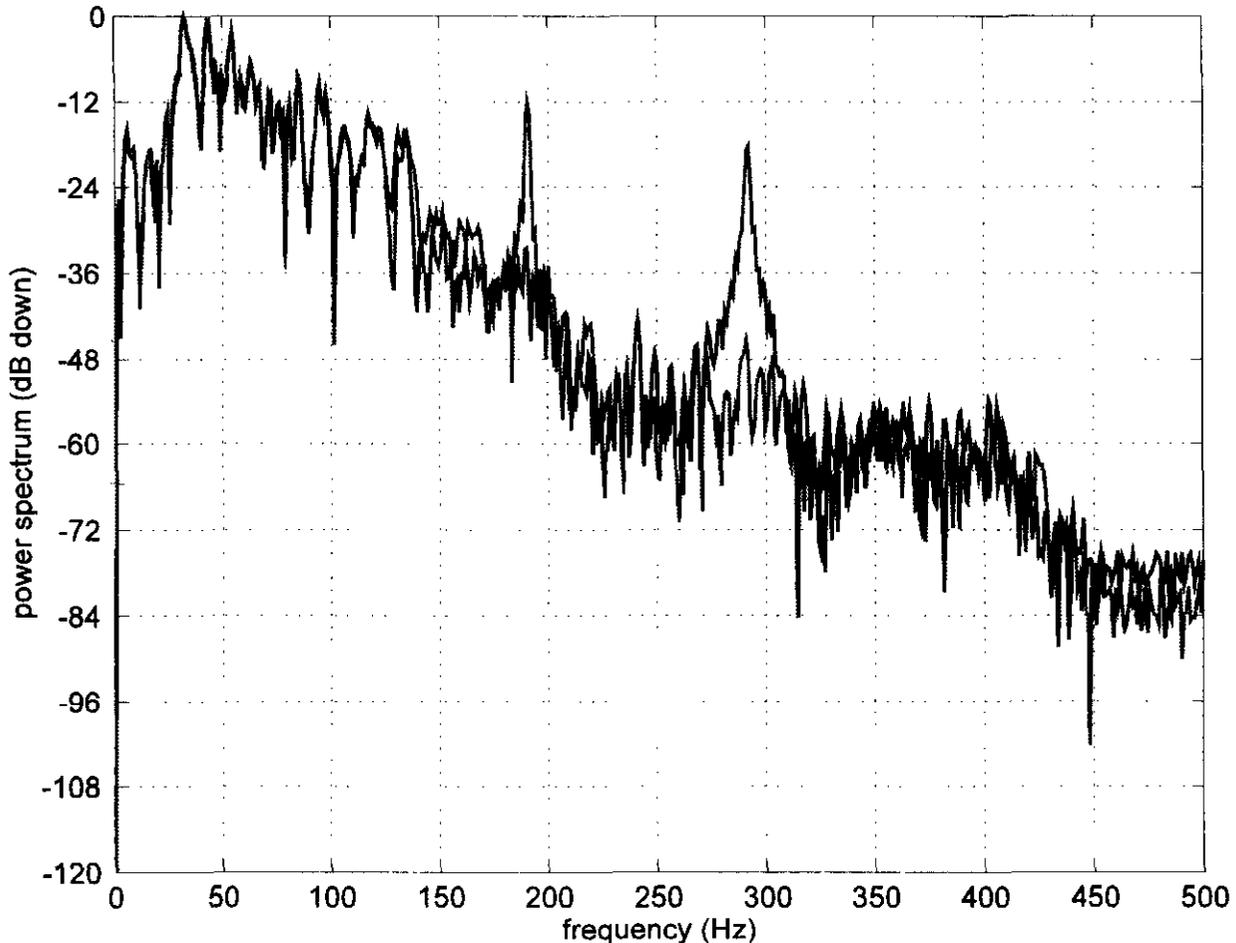
We can measure spurious frequency quite easily in the laboratory by employing a horizontal miniature shaker. This is built up from an elastically suspended frame (Fig. 4) containing a clamp for the geophone being tested and a pair of driver geophones mounted perpendicular to the test element. The total moving mass of this horizontal shaker is approximately 23 grams. By applying a frequency sweep to the driver elements, and observing the voltage signal from the test element the discontinuity in the amplitude response can be observed. Alternatively noise and a spectrum analyzer can be employed. The relative phase of the drivers and test element signals can be observed with the Lissajous method, also indicating the resonance frequency. Even a crude

mechanical tick on the side of a suspended element will usually provide a measure of the resonance frequency. Figure 5 is an example of a spectrum analyzer screen showing the spurious frequency peak.

The above method provides the resonance frequency however the amplitude of the signal is less easy to measure. The amplitude of the spurious frequency depends on the incidence angle of the signal polarization relative to the orientation of the spring arms. In rotating coil geophones this is random because the spring's orientation is not indexed to the outside of the geophone element. At specific angles of horizontal actuation, spurious frequency can be difficult to measure with this method.

To improve the ability to measure spurious frequency a new laboratory method was developed. Tests were set up to compare the spurious frequency measured with the conventional method described above and with a rotational impulse

**Power Spectrum**  
**Shot 24, Channel 3 & 4, Window 500-1000ms**  
**Traces normalized separately**



**Fig. 10.** Power spectrum of channels 3 and 4 from shot 24 (Fig. 6).

suspension employing the GeoPinger. A GeoPinger is a device developed for measuring geophone case-ground coupling consisting of a piezoelectric (PZT) crystal which is used to provide a very repeatable broadband impulse to the geophone case. A configuration of 3 PZT crystals (Fig. 6) mounted in a symmetrical fashion applies a very short duration mechanical rotational force on the geophone mass-spring system. The result is a very clear peak measurement without endlessly rotating the geophone in the conventional horizontal test-jig in order to find possible other/lower resonances. Measurements using the GeoPinger and rotational spurious jig give unambiguous results in one step.

The amplitude and frequency of the spurious resonance can be shown to be a function of coil position. As the coil is displaced and the spring arms move from their flat position it requires less force to move the coil in a cross axis direction. Effectively the cross-axis spring stiffness becomes less as the

coil is displaced and the arms become more bent. The relationship is such that at the coil position where the spring arms are flattest we will see the maximum spurious frequency and minimum amplitude (or sensitivity to cross-axis forces). As the spring deforms with increasing coil excursion the spurious frequency becomes lower and the sensitivity to cross axis forces increases, producing a higher amplitude peak (Fig. 7). In this case the minimum spurious amplitude and maximum frequency coincide at about 10% of coil excursion, indicating that the coil was hanging slightly low from the mid point of the p.p. coil excursion.

This is a very important relationship as it helps explain why we see the spurious frequency when large amplitude signals are applied to the geophone, causing greater coil excursion and hence facilitating setting up the spurious resonance. Coil position changes when geophones are tilted, the coil moving as the balance between gravitational forces on

**Power Spectrum**  
**Shot 24, Channel 3 & 4, Window 500-1000 ms**  
**Traces normalized separately**

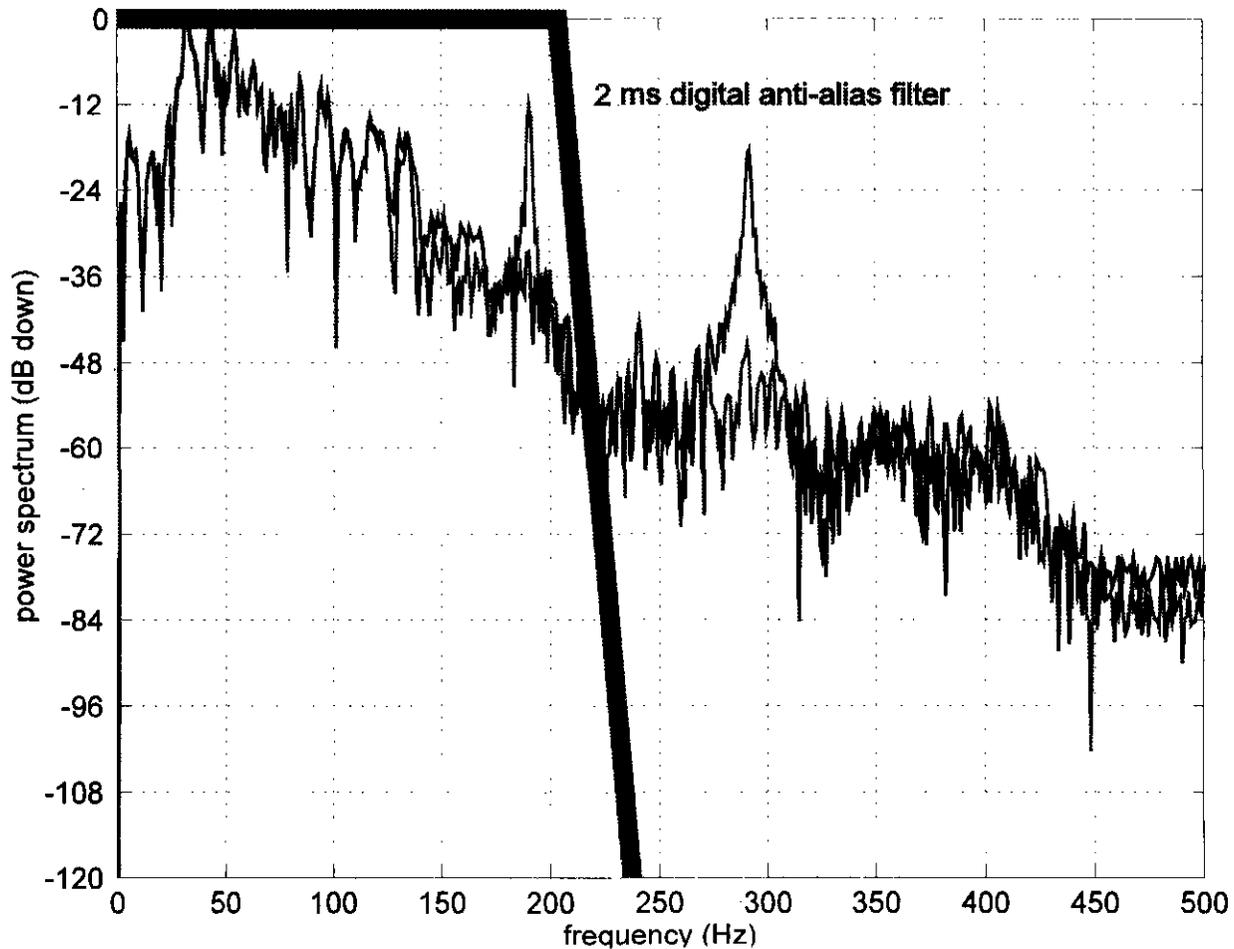


Fig. 11. Power spectrum of channels 3 and 4 from shot 24 with a simple 2 ms anti-aliasing filter superimposed.

the coil and the spring preform (or pre-load) change. In vertical geophones the coil rises as the case is tilted. In practical terms this means that a tilted geophone will be more susceptible to spurious frequency onset.

#### FIELD TESTS

The objective of the first test was to collect some spurious frequency contaminated seismic data. The second field test was performed to see if there is a relationship between seismic energy levels and the spurious frequency occurrence, a closer simulation of actual field data. Our two field tests were conducted in the Wassenaar area of the Netherlands and the results follow below.

##### Field Test 1:

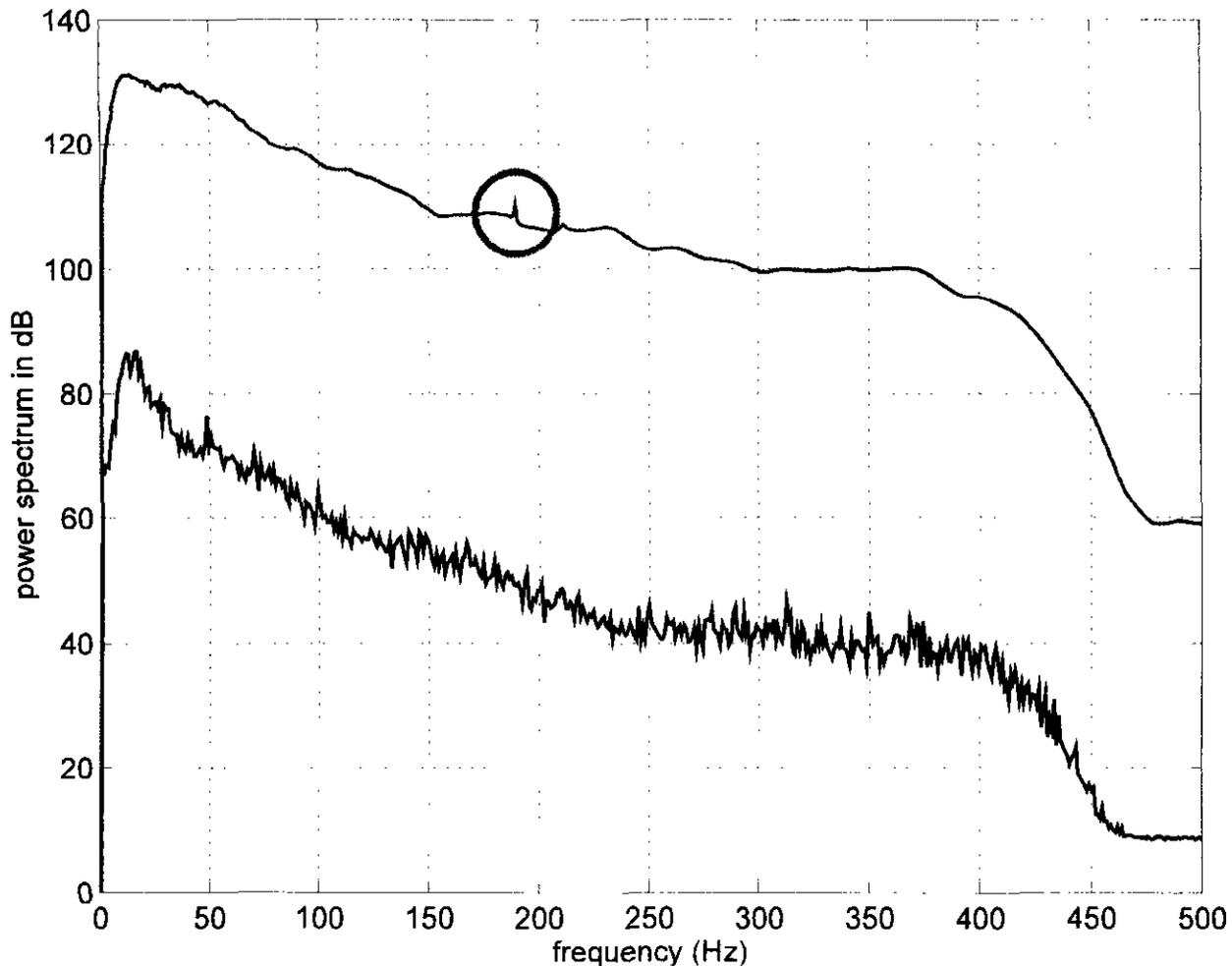
The receiver and shot point pattern was designed to provide a high likelihood of generating spurious resonance in the

recorded data. To show the varying effect of frequency on seismic data, two types of geophones were planted in an alternating sequence. The actual geophone spacing was <10 cm and, knowing the randomness of the coil rotational position inside the sensors, they were planted in a circular pattern of 1 m radius. Shots (detonators) were fired sequentially round a concentric path at a greater radius (5 m). This arrangement was adopted to provide a wide range of azimuths on all the geophones per shot and so that each geophone received arrivals from a wide range of shot azimuths. The 24 bit sigma-delta Bison Seismograph recording system was set to record at 1 ms sampling rate with anti-alias at 412 Hz, well above the spurious frequency of the geophones tested.

The circular spread and shot point pattern appeared to be successful, nearly all traces showing some form of spurious frequency contamination. Figure 8 is an example of the data from shot 24, showing some evidence of spurious frequency

## Power Spectrum

### All shots, Channel 22 & noise, Window 0-1000 ms



**Fig. 12.** Power spectrum of all the data (upper line) in field test #2 and only channel 22 (lower line) for a window including the first breaks. The spurious frequency is circled.

on channel 36. Channels 3 & 4 were used for further processing. Figure 9 is a section of channel 3, shot 24, with a 190 Hz sine wave superimposed. In the enlargement it is quite clear that this frequency exists in the data.

The two types of geophones were deployed and the spurious frequency of each geophone type was seen. Figure 10 shows two channels, 3 & 4, superimposed. Channel 3 was recorded with a lower spurious frequency geophone and shows a clear peak at 190 Hz. Channel 4 was recorded with a higher spurious frequency geophone (24 bit), shows its peak at 290 Hz. It is clear that the higher frequency geophone can move the spurious frequency well above the 200 Hz anti-alias filter of a modern recording system (Fig 11). In processing the data it was necessary to window the data to exclude the first breaks to make the spurious frequency clearly visible.

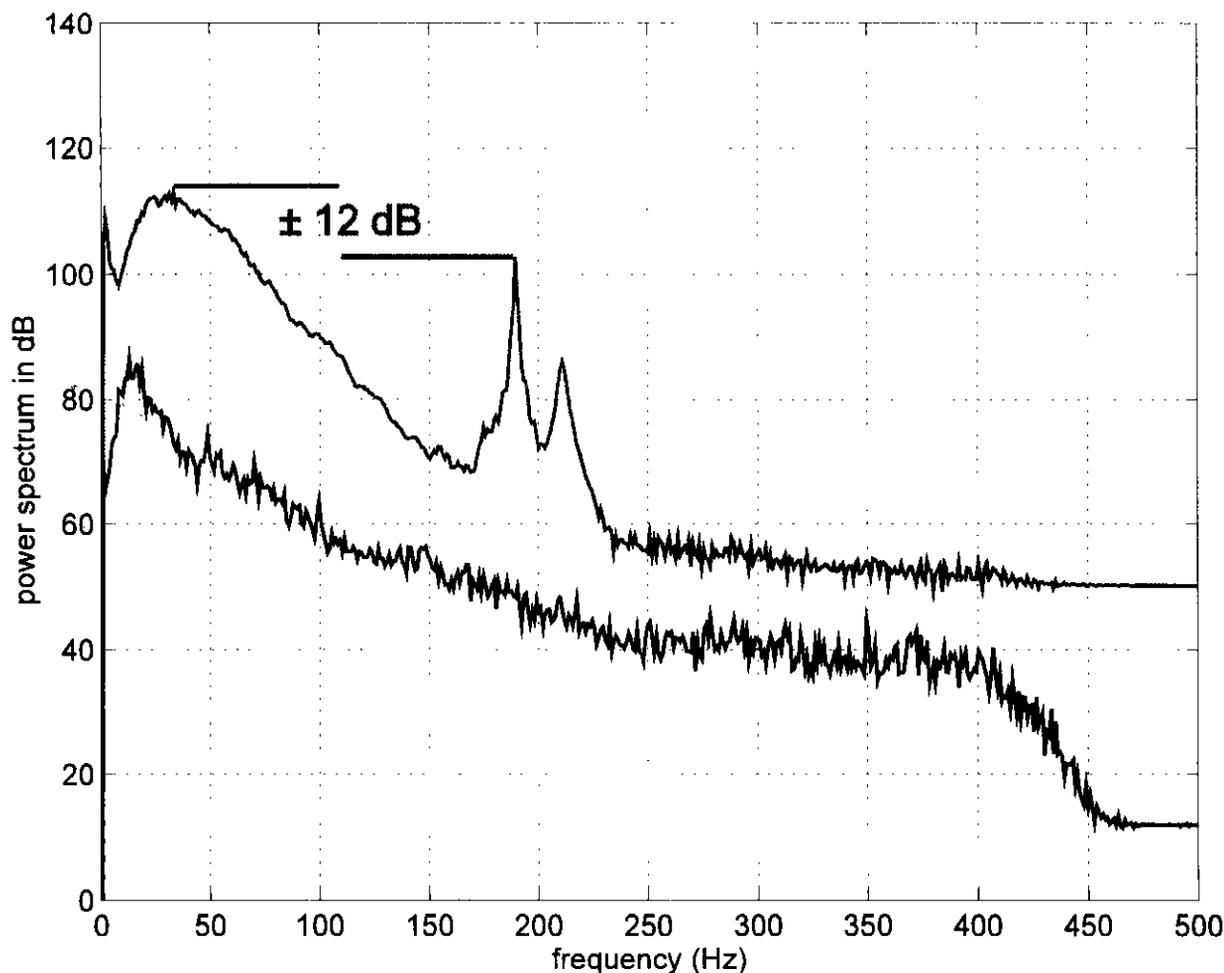
#### Field Test 2:

Based on the previous test the range of azimuths could be reduced and so the geophones were planted in a half circle. Three shot point lines were arranged at 0, 45 and 90 degrees with varying offsets from 1 to 25 m.

To observe the general effect on the data, one channel was picked out. All data shot into this receiver was transferred to the frequency domain and averaged. Shots that showed clipping of geophone or recording system were not included. As a result of this averaging the response becomes very smooth and will be only indicative for the overall frequency content of this channel (Fig. 12), there is a peak showing an indication of the spurious frequency. However when we looked at the same data but excluding the first breaks by placing a window from 200 - 1000 ms, the dramatic effect of the spurious frequency

## Power Spectrum

### All shots, Channel 22 & noise, Window 200-1000 ms



**Fig. 13.** This figure is identical to Figure 9 except now the window does not include the first break. The effect of geophone created spurious frequency is amplified in this situation.

becomes very apparent, (Fig. 13). Note that the average seismic peak amplitude is only 12 dB above the spurious resonance energy.

#### CONCLUSIONS

Our results show that geophones should be chosen with a spurious frequency higher than the anti-alias frequency of the system to be used to record the data. Care must be taken when changing anti-alias frequency even if the sample rate is kept constant. Geophone placement is important in that tilted geophones are more susceptible to spurious resonances. We cannot presume that just because our source energy is cen-

tered on 30 to 60 Hz that we will have no problems with spurious frequency at 3 to 4 times this centre frequency. Under the wrong conditions even low frequency energy may provide enough lateral movement in the geophone to cause spurious frequency ringing in the seismic data.

#### REFERENCES

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- Edelmann, H.A.K., Faber, K., Maxwell, P.W., 1994, Modern geophones, do they meet the demands of shallow seismic measurements? Abstract, 64th SEG Convention, Los Angeles, October 1994.