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Optimized harmonic noise reduction in vibratory seismic data

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Due to non-linear phenomena and coupling problems, Vibroseis acquisitions often suffer from source signal distortion that can cause a remarkable decrease of the signal-to-noise ratio. Such phenomenon can become particularly problematic when slip-sweep techniques are adopted in order to improve acquisition productivity. In such conditions harmonic distortion due to a shot can in fact mask fundamental energy belonging to the previous shot. In order to reduce the unwanted noise contamination an evolutionary-algorithm based optimization scheme is introduced into the harmonic noise estimation scheme. The effectiveness of the implemented noise attenuation procedure is shown on synthetic and field datasets.

Keywords: noise, filtering, optimization, slip sweep

1. Optimization scheme for harmonic noise estimation

The slip-sweep vibratory acquisition method can help to increase productivity and/or quality of seismic data if the harmonic distortion caused noise is sufficiently removed from the seismic records [BAGAINI, 2006; LEBEDEV, BERESNEV 2004; MEUNIER, BIANCHI 2002, 2005]. In the published techniques first the harmonic noise components are estimated relative to the fundamental source signal, then the harmonic noise content is calculated enabling the subtraction operation to be carried out.

The estimation problem can be tackled in terms of amplitude of the upper harmonics with respect to the fundamental one. Analyses show that upper-harmonic amplitudes are frequency-dependant values [SCHOLTZ 2002; 2003; 2004]. A *ratio trace*, defined as the ratio between a given

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upper harmonic and the fundamental one can be adopted [SCHOLTZ 2002, 2003, 2004],

$$R_n^m(f) = \frac{V_m(f)}{V_n(f)} \tag{1}$$

where V is the contribution of the m and n harmonics (in our case n is the fundamental one).

The fundamental harmonic (that some authors define as *first* harmonic) is basically represented by the theoretical sweep used as input (commonly named ‘pilot sweep’). When we correlate the observed trace with the harmonic component n and mute the data outside a window centered on the main peak we somehow isolate the contribution due to that harmonic. If we then divide the resulting quantity by the conjugate of the considered harmonic we get back to the previous uncorrelated status but having removed the contribution of all the other harmonic components. Estimation of the contribution of the upper harmonics can be performed by minimizing the following expression:

$$\frac{[T \otimes P_n]}{P_n^*} - \frac{[T \otimes P_0] * R_0^n}{P_0^*} \Rightarrow 0 \tag{2}$$

where P_0 represents the pilot sweep (fundamental harmonic), P_n the distortion due to the nth harmonic, the square brackets denote the muting of the data outside the window centered on the main peak and $\otimes$ represents correlation. In order to obtain an expression easier to handle, Eq. [1] can be also rearranged as

$$[T \otimes P_n] \otimes P_0 - [T \otimes P_0] * R_0^n \otimes P \Rightarrow 0 \tag{3}$$

The first part pertains to the observed data, the second part to the *ratio trace* to be evaluated.

Phase differences between upper and fundamental harmonics are often reasonably constant (at least for most of the considered frequency range) and a constant value for each harmonic can thus be often sufficient to describe their behaviour. By considering the upper-to-fundamental harmonic ratio and an optimization procedure based on Evolutionary Algorithms (EAs) we attempt to attenuate upper-harmonic components. Evolutionary algorithms belong to the family of heuristic optimization tools and have been successfully adopted for a number of geophysical problems [e.g. NIKRAVESH et al. 2003; DAL MORO, PIPAN 2007]. Their main (but not unique) advantage consists of being little prone to local-minimum failure thus resulting particularly suitable for complex problems hard to be solved with gradient-based methods. By means of an upper-harmonic forward modeling based on the analyses presented in SCHOLTZ [2002; 2003; 2004], we designed an EA-based tool to minimize the energy in the portion of the seismic trace where upper harmonics occur.

The cost function is then defined as the mean amplitude of the difference between the actual trace (containing the upper harmonics and possibly primary signal(s)) and the estimated one (that contains only upper harmonics as predicted from the pilot sweep via the EA-based procedure). Amplitude ratio (see Eq. [1]) curves are discretized into a limited, but sufficient, number of frequency–amplitude points and linearly interpolated along the entire considered frequency range (*Fig. 1*).

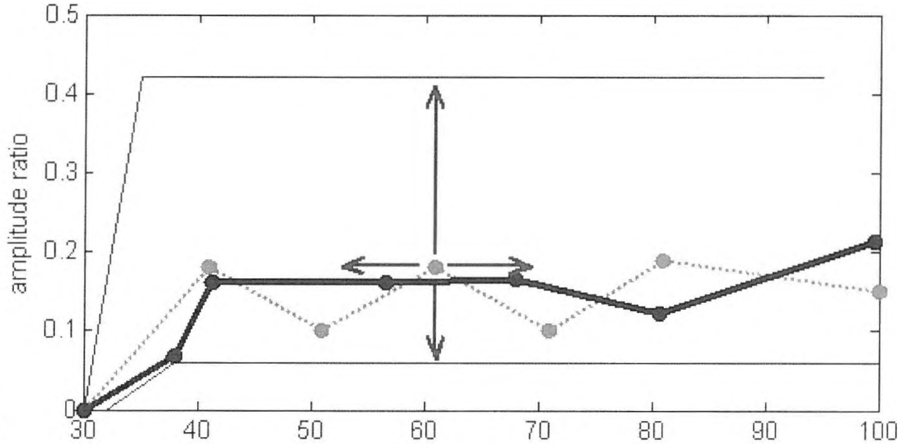

Fig. 1. Discretization of the amplitude ratio curve. Light-gray dotted line: the model used as starting point for the genetic search. Each point is free to move both vertically (amplitude) and horizontally (frequency). Thick black line: final model. Also reported the search space where the solutions are sought

1. ábra. Az amplitudó hányados görbéjének megadott pontjai. Szürke pontvonal: a genetikai algoritmus kiindulási pontjául használt modell. Minden pont szabadon mozoghat függőleges (amplitúdó) és vízszintes (frekvencia) irányban. Vastag fekete vonal: végső model. Adott a tartomány is, ahol a modell megoldást kerestük

Main input data are the number of harmonics to consider, the search space within which seeking the optimal solution, the size of the population, the generation number and the time of occurrence of the first arrivals (required to separate the so-called *positive* and *negative* times). The implemented toolbox was tested both on synthetic and field datasets.

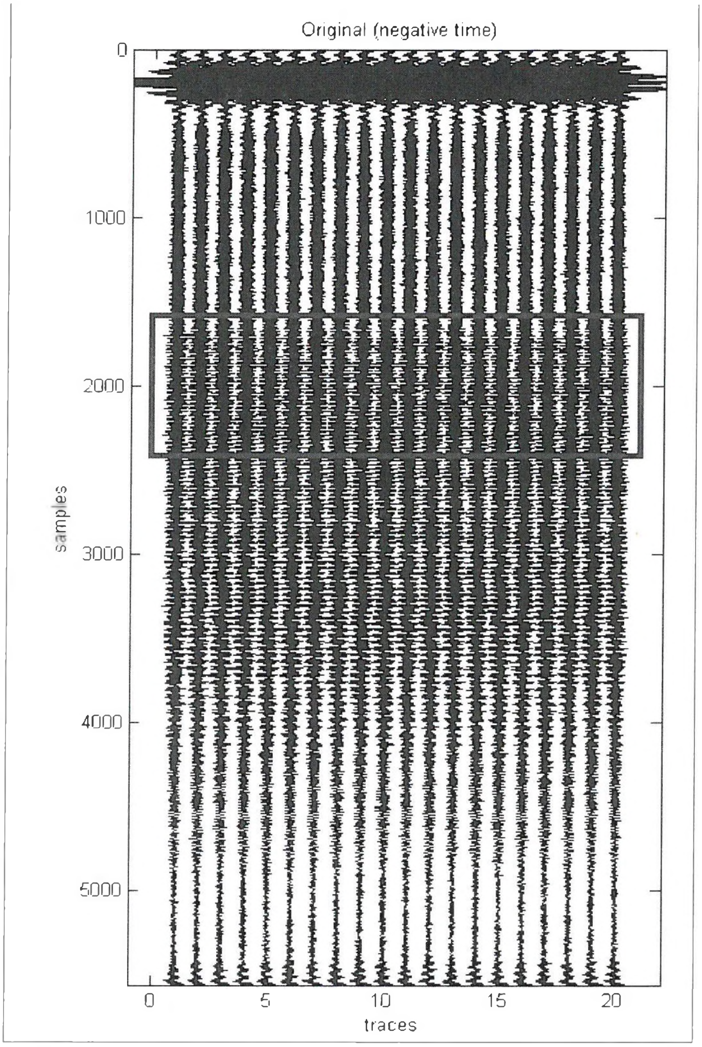

Fig. 2. Synthetic dataset (correlated with pilot sweep): in the rectangle the area of the data where a primary signal is severely obscured by upper harmonics and random noise

2. ábra. Szintetikus adatrendszer (elméleti vibrojellel korrelálva): A négyszögben azt az adatrészt jelöltük, ahol az elsődleges jelet a felső harmonikusok és a véletlen zaj lényegesen elfedi

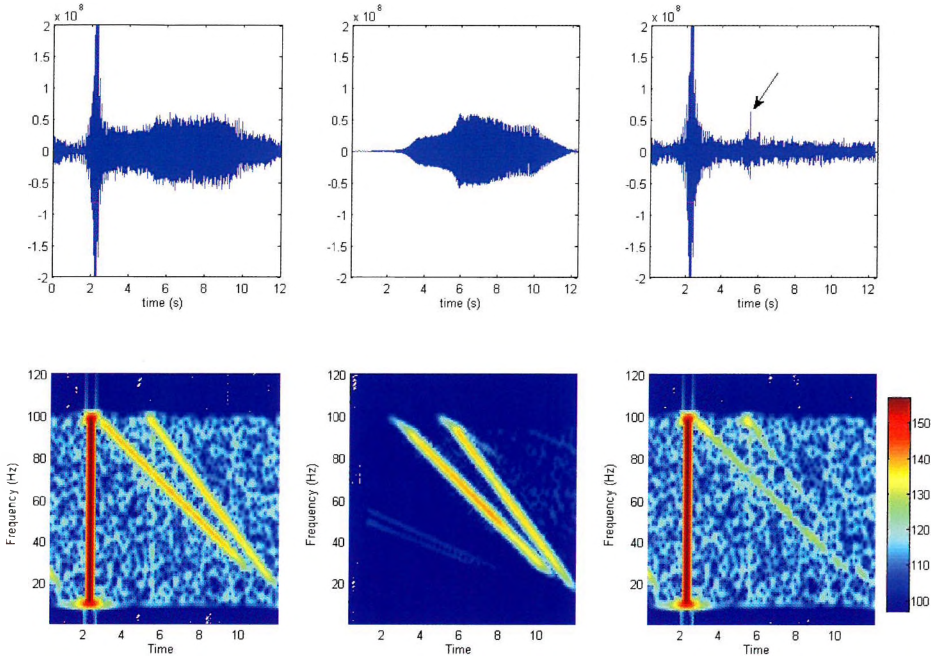

Fig. 3. Synthetic dataset. From left to right: original trace (above) and its spectrogram (below), estimated upper harmonic components, trace obtained by subtraction of this latter from the actual trace

3. ábra. Szintetikus adatrendszer. Balról jobbra: eredeti csatorna (fent) és spektrogramja (lent), becsült felharmonikus komponensek, ez utóbbinak az aktuális csatornából történő levonása után keletkezett csatorna

2. Synthetic dataset

A synthetic dataset (*Fig. 2*) was created by considering first two upper harmonics with frequency-dependant amplitude up to 15 and 25% respectively of the fundamental one and constant phase difference (–0.5 and 0.5 rad). Two events were included: a first arrival with no move out and a weaker later event with amplitude equal to 1% of the first one and with a linear move out. Random noise with maximum amplitude equal to the second event was also added.

Results of the EA-based processing are reported in *Figs. 3* and *4* where the comparison between spectrograms and traces before and after data processing show the effectiveness of the designed optimization scheme (notice the small signal previously obscured by the harmonic and random noise and put in evidence by the processing). Depending on the amount of added random noise upper harmonics are attenuated by 15 to 25 dB.

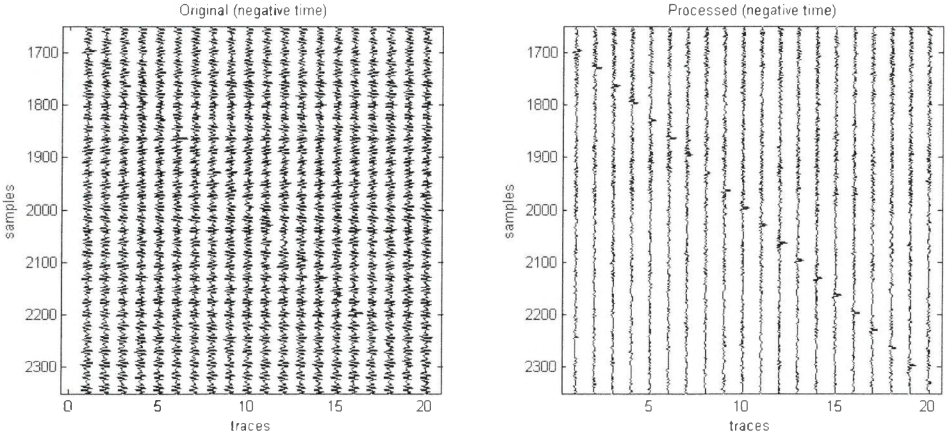

Fig. 4. Data region where a weak signal is obscured by harmonic and random noise (rectangle in Fig. 2), before (left) and after (right) the designed optimization procedure is applied

4. ábra. Adattartomány, melyben a harmonikus és a véletlen zaj elfedi a jelet (a 2. ábrán négyszöggel jelölt terület), mielőtt (bal oldal) és miután (jobb oldal) a kijelölt optimalizációs eljárást alkalmazták

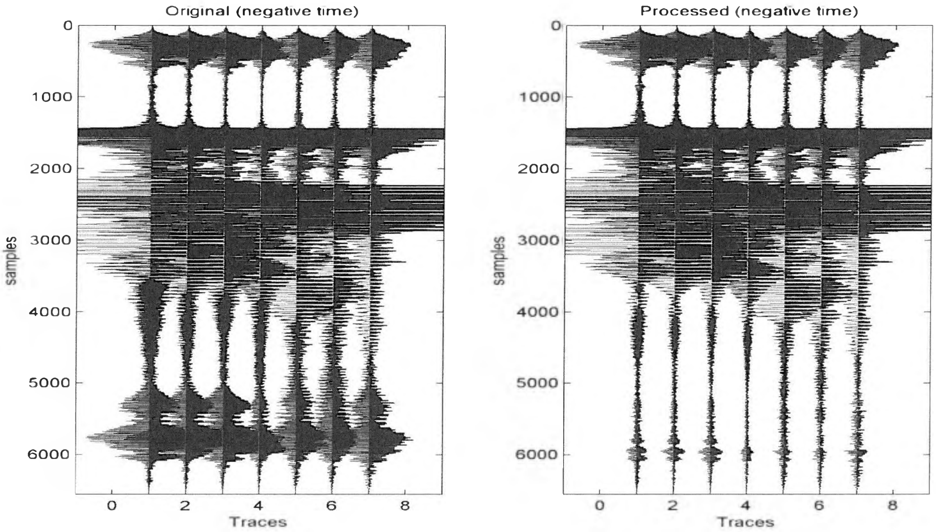

Fig. 5. Field dataset: original (left) and processed (right) traces
5. ábra. Terepi adatok: eredeti (balra) és feldolgozott (jobbra) csatornák

3. Field dataset

A field dataset acquired by ELGI in the framework of the ASAP project was considered. Results of the processing are reported in *Figs. 5* and *6* and show the attenuation of the energy due to upper harmonics (spectrograms show upper harmonic attenuation of about 15 dB).

4. Conclusions

It can be appreciated that the *ratio trace* approach (on which the present optimization schemes are based) can be proficiently adopted to handle the problem of harmonic distortion attenuation. Even if harmonic distortion can vary from trace to trace, in order to avoid problems related to instabilities due to other sources of noise, the basic entity to consider when reducing its energy is probably the common shot gather (characteristics of upper harmonics should be evaluated as average values for several traces). In this perspective stochastic optimization can provide a suitable family of

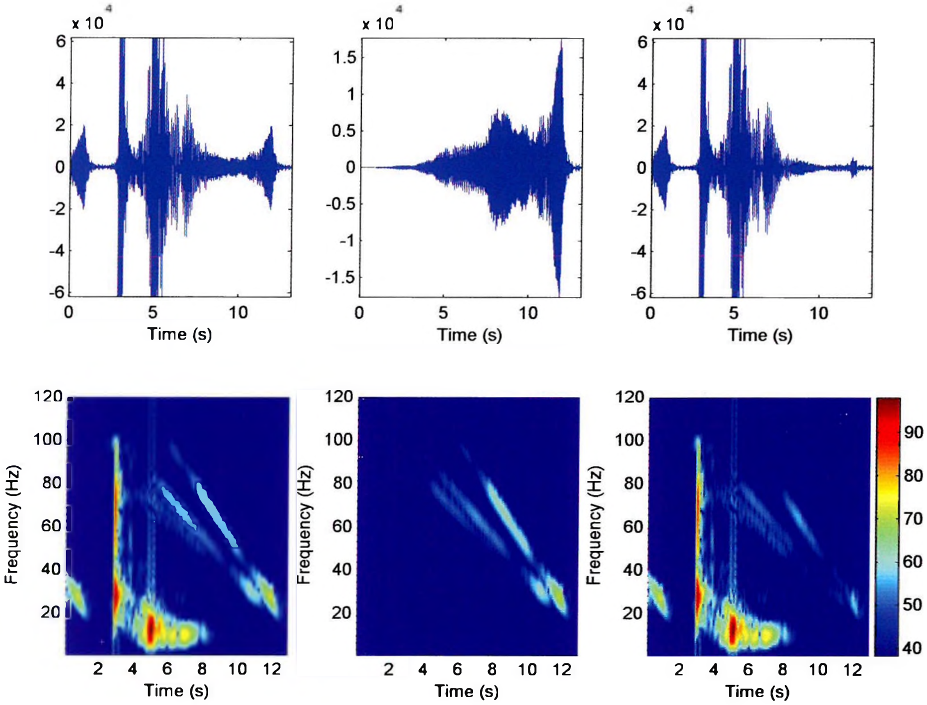

Fig. 6. Field dataset. From left to right: actual trace (and its spectrogram), estimated upper harmonic components, subtraction of this latter from the actual trace

6. ábra. Terepi adatok. Balról jobbra: aktuális csatorna (és spektrogramja), becsült felharmonikus komponensek, ez utóbbiak és az aktuális csatorna különbsége tools to handle the problem of several-trace datasets and the results presented in this study show that such approach can be successfully applied.

It can be underlined that in spite of some theoretical considerations, performance comparison between an approach based on the minimization of all the harmonics at once (energy minimization in the negative times) and a strategy to handle the different harmonics one by one (energy minimization of the correlation peak) so far shows no clear superiority of the second strategy (theoretically neater).

Further improvements currently under study regard a formulation able to limit as much as possible the use of the convolution in the forward modeling adopted in the optimization scheme (so to decrease the computational load) and a more complex way to handle the phase to allow frequency-dependent phase variations.

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Optimalizált harmonikus zajcsökkentés vibroszeiz adatokon

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A vibroszeiz mérések gyakran szenvednek a forrásjel torzulásától, a nemlineáris jelenségek és csatolási problémák miatt, ami jelentős jel-zaj viszony csökkenést képes okozni. Ez a viselkedés különösen problémássá válik, amikor a slip-sweep mérési módszer kerül alkalmazásra a mérés produktivitásának fokozására. Ebben a helyzetben a jelgerjesztés által létrejött harmonikus torzítás valóban képes elfedni az előző rezgéskeltéshez tartozó alapharmonikus energiát. A nemkívánatos zaj csökkentésére, a harmonikus zaj meghatározási folyamatába, egy evolúciós algoritmusú optimalizációs séma kerül bevezetésre. A megvalósított zaj elnyomási eljárás hatásossága szintetikus és terepi adatrendszereken kerül bemutatásra.