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SEISMIC SOURCE SELF-ORGANIZING

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Abstract: In the paper the results of the frequency analysis of the elastic pulses from the loaded rock sample source models, of the rockbursts records and of the seismograms of selected shallow earthquakes are presented. For all the three categories of study the fundamental symptoms of non-linear processes in seismic foci were found and demonstrated as clearly pronounced. Namely, the modulation of elastic waves generated in the source under load, the self- synchronizing the individual components of the wave field and the coherent wave radiation were repeatedly observed which can be understood as the precursors of the final stage of elastic radiation in which the shift of the maximum in frequency spectra to lower values occur, what is reflected in a release of the maximum amount of seismic energy. All this indicates that the non-linear processes can participate in a seismic source during the energy release. Also, certain weak points of "linear" theories of the seismic source (such as, e.g., the seismic source size, etc.) can be easily understand and explained from the view point of non-linear dynamics.

Key words: seismic source physics, frequency analysis, non-linear dynamics, self-organizing processes.

1. INTRODUCTION

In the last 20 years numerous theoretical models of a seismic source were introduced and applied for the solution of individual seismic events, see, e.g., J. N. Brune (1970), J. N. Brune at al. (1979), V. Grösser at al. (1979), R. Madariaga (1976) and V. Rudajev (1986). These models were altogether based on the physics of linear dynamics, in which the principles of wave superposition ruled the process of interaction and interfering the seismic waves. As the fundamental characteristics of a seismic source the following parameters have been considered. Size of a seismic source (volume V, radius r, length l), magnitude M, stress drop $\Delta \sigma$, Burger's vector $\bar{u}$, seismic moment M_o, slip velocity v_{sl}, rupture velocity v_r, source radiation characteristics, and time t of the displacement iniciation and propagation.

In the classical concepts of the seismic source models the increase of the earthquake magnitude is explained by the increase of the source volume/dimensions (see, e.g., Sadovski 1984, Brune 1970). Further, the observed narrowing down the spectra and growth of the wave period T as a function of increasing magnitude M is believed to occure due to the extending the time (duration) of seismogenic processes in a seismic foci.

As for the natural events, however, the seismic size (volume) computed from spectral properties of radiated waves, as shown e.g., in the works of Brune (1970) and R. Madariage (1976) reached unrealistically large values, especially as concerns the large earthquakes, $M > 6$. To reduce this apparent disagreement between observed and computed focus size, an the artificial coefficient K was introduced, what actually ment that the shear wave velocity β value was in the computations reduced 5 to 10 times.

These observed changes of the frequencies in the relation to magnitudo can be explained also using the supposition of nonlinear processes in the seismic source. This supposition has its response in the nonlinear superposition of seismic waves (amplitude modulation, coherent radiation, narrowing down the spectra).

These mentioned characteristics, connected e.g. with non constant displacement velocity in the seismic source, were observed in the large scale of radiated seismic energy - from SA pulses, rockbursts, to the earthquakes.

2. THE NONLINEAR EFFECTS RESPONSED IN RADIATED WAVES

Linear approach, which is mostly used up to date, is based on the principle of superposition of radiated waves, i.e. the resulted seismic signal is done by the summation of the signals of the individual elementar sources :

$$Y = \sum_{i=1}^{n} Y_i$$

The principle of superposition of the seismic waves is valid in the case of constant displacement velocity in the source and when the focus is situated in the Hooke's medium.

In the case of the non constant displacement (rupture) velocity or the non-Hooke's medium, the principle of superposition is not generally valid, and the relations of nonlinear physics can be used. These facts resultes to the amplitude modulation of seismic radiated signals from individual sources, what can be described as follows :

$$Y = a_o \; [1 + m.f(t)] \; sin \; (\omega_o t + \phi_o),$$

where $sin\ (\omega_o t + \phi_o)$ is modulated signal and $f(t)$ is modulating signal, m is called the modulation depth. This is reflected in the spectral pattern of resulting radiation: instead of the two frequencies characterizing both inter-acting radiations, the three frequencies will occure. Namely, the frequency f_o (= $\omega_o/2\pi$) of modulated radiation and two other (satelite) frequencies $f_o \pm \Delta f$; the value of Δf is the frequency of modulating radiation $f(t)$, after Kharkievich, 1953.

Another phenomenon important in non-linear dynamics is the principle of forced synchronization, firstly discovered by Huygens on the behaviour of mechanical systems, later explained by Poincaré (1928) and Mendelstham (1950) on the platform of non-linear differential equations. In the recent works, see e.g., Nicolis (1986), the effect of self synchronization is sometimes called 'self-organizing'. Commonly, it can be described as follows: During mutual interaction of non-linear oscillators the mutual energy exchange occurs. Gradually, due to internal relations, the energy interchange results into the oscillation phases synchronization. Finally, a coherent radiation is established. During this process, the energy of the wave field growths considerably, because as concerns coherent radiation its energy W is proportional to the square number of interacting oscillators $W \sim \Sigma\, n^2$ in contrast to non-coherent radiation for which $W \sim \Sigma\, n$.

After Nikolis (1986), during such a coherent radiation, the value of frequency can decrease.

The physical processes in a seismic source propagate with variable displacement velocity (slip velocity) and therefore the elementary source oscillators mutually interchange their energy, what is reflected in the variations of their phases, so that the resulting radiation can be properly described in terms of non-linear dynamics.

In the following an attempt is presented to detect the principles of seismic source self-organizing in a wide range of energy release levels: these levels extend from the seismoacoustic emission recorded in laboratory, up to tectonical earthquakes.

3. LABORATORY EXPERIMENTS

An extent series of laboratory experiments on biaxially loaded rock samples was performed in order to detect the symptoms of non-linear processes described above.

As physical models triples of rectangular blocks of magnesite were used, see Fig. 1. The blocks were located in a special model structure, in which they were subjected to confining force P_2. After fixing the desirable value of the load P_2, the models were pressed by load P_1 so that the inner block was pressed against the outer blocks. Prior to loading, two pick-ups were fixed on the model surface, one (No.1) in the vicinity of the displacement plane, the other (No.2) across it. Pick-up No.1 was an accelerometer and recorded acoustic emission, pick-up No. 2 was of a gauge type and recorded the mutual displacement of model blocks.

Load P_1 was uniaxial, linearly increasing force. It was applied up to the values of cca 60 kN (which corresponds the stress value σ_1 = 20 MPa). Loading rate was cca 500 N s^{-1}. It was expected that in the course of increasing the P_1 compression fast seismogenic displacements along the displacement plane would occur.

Confining load P_2 was fixed in several load levels, with a step of approx. 3.3 kN. After fixing the P_2 load and increasing the P_1 load, seismogenic displacements occurred. The emited seismic pulses were recorded by pick-ups Nos 1, 2 and stored in transient recorder DL 912 in the digital form. Sampling rate was 10 MHz. The dead time (during data transfer) was 0.2 s. The FFT analysis of the recorded pulses was performed by means of current routines.

In the given set up of the experiment, the required conditions of mechanical friction coupling were satisfied, what resulted in stick-slip occurrence. Let us have a look at the wave form of the pulses radiated by the stick-slip instabilitites. Coming from the level σ_2 = 3.0 MPa to level σ_2 = 4.65 MPa, we can see a stress formation of the originally complex/chaotic wavefield consisting of numerous frequency components into a more simple, monochromatic-like waveform in which the high-frequency components appear only in the front part of the pulse. At the last P_2 level (σ_2 = 5.2 MPa) the wave form resumes a more complex type again, see Fig. 2. An interesting tendency can also be seen in the pulse envelope curves as related to individual P_2 levels. From the level σ_2 = 3.0 MPa up to level σ_2 = 4.65 MPa a clear tendency can be detected from the originally chaotic pulsation of the recorded signal to a clearly modulated one. This modulation disappears for the pulses recorded at level σ_2 = 5.2 MPa.

The above features are clearly reflected in the amplitude frequency spectra of these pulses, see Fig. 3: going from the 1. level (σ_2 = 3.0 MPa) over the 2. level (σ_2 = 3.55 MPa) the individual spectra harmonics merge; this makes the spectra more simple, which physically means more coherent. This effect culminates at the 3. P_2 level (σ_2 = 4.1 MPa), characterized by a nearly monochromatic spectrum (f_{max} = 36 kHz) with well pronounced satellite components. For the 4. level (σ_2 = 4.65 MPa) this monochromatic behaviour is still preserved, however, the frequency maximum is shifted from 36 kHz, the spectrum satellite components being quite markedly expressed. At the last 5. level (σ_2 = 5.2 MPa) the previous self- organizing of the wave field is lost and the spectrum resumes to its initial complex/chaotic state.

The aim of the second series of laboratory measurements performed was to verify whether the dependences obtained in the previous measurements (on magnesite samples) will be true also for the other rock materials, model sizes and contact conditions. As for the rock media fine grained sandstone (grain size smaller then 0.5 mm) and coarse grained sandstone (grains 4-8 mm) were tested. Concerning the model size, the structures of 150x150x60 mm and 40x40x60 mm were treated; in such a way the models of larger and smaller dimensions were investigated than these magnesite ones of the first series. Two types of the contact surfaces were tested, namely the ordinary surface obtained after the sample cut by a diamond saw, and, secondly, the fine polished, contact surfaces. The experimental set up was the same as the previous arrangement of the measurement on magnesite samples. As concerns the confining load P_2 it was kept constant for all the experiments being selected within the zone of stick-slip seismic source character.

In Fig. 4 the two examples of pulses (and their spectra) from loaded magnesite models are given. The left hand pulse is characterized by a non-coherent radiation with the wide/complex spectrum and relatively low amplitude. The right hand pictu represents another type of the pulse, already modulated, what is reflected in clearly expressed satelite spectra components.

Also the two series in Fig. 5 presenting the pulses radiated from loaded model composed of fine grained sandstone (Upper series, pulses 1 - 3) and of coarse grained sandstone (bottom series, pulses 4 - 6) demonstrate the typical stages of seismic energy release revealed already in the measurements on the magnesite models. Independently on the grain size of both the rock materials, the radiated pulses are (firstly) characterized by a low intensity and by spectra with numerous local maxima, see the two pictures in the first collumn of Fig. 5. An increse of the amplitude is evident in the middle collumn of the picture in which the pulses with modulated wave-pattern are shown. The pulses given in the third collumn of the picture present fully coherent radiation for all the rock materials.

Also, a clear shift of the maximum amplitude spectral component to lower frequency values is clearly seen in Fig. 5 : from app. 80 kHz to app. 40 kHz for the fine grained sandstone (see the upper series, the second and third record) and from for app. 112 kHz to app. 16 kHz (7 times) for the coarse grained sandstone, bottom series, second and third picture).

The componental difference (grain size) of both the rock materials are well reflected in the discussed spectra. For the coarse grained sandstone the radiation works on higher frequencies, because the stress concentration is considerably higher on the large grain contacts of the border face in comparison with, more or less, regularly distributed stress field along the contact sample faces for the fine grained sandstone. According to this, the shift of the frequency maxima to lower values is larger for the coarse grained sandstone model.

Thus, it is demonstrated here, that the frequency recorded does not depend on the dimensions of the focal zone, but on the state of the rock, on its composition and on the contact conditions along the seismogenic fault.

The results obtained clearly demonstrate strenghtening the non-linear processes as a function of confining pressure; as it increases the spectrum of radiated waves becomes more simple, see the levels 3 and 4 in Figs 2 and 3. This phenomenon reflects the growing degree of generated oscillations' coherency. In this phase of loading the "satelite" local maxima in amplitude spectra occur as well as the shift of the frequency of maximum amplitude to lower frequencies what fits well the Poincaré/Mendelstham theory. In the highest degree of the coherency of radiated oscillations the energy of the wave field reaches its maximum value. Further, loading the model results in the return of coherent wave field into its initial chaotic state. All this speaks in favour to non-linear processes in a seismic source simulated in laboratory conditions.

4. ROCKBURST FOCI IN MINES

The rockbursts belong to the typical seismic phenomena which occure as a result of interaction between the tectonical stress field changes and an undeground man-activity. The time pattern of the focal zone fracturing can hardly be described by means of simple physical models in most cases because the rupture process cannot be explained by a force dipole only, in contrast to the tectonic earthquakes. The natural space distribution of stressed in a rock massif which interferes with the effects of local stress redistributions due to mining excavation (exploration), results into a complex way of fracturing and also to the time-variable radiation of seismic energy. The time pattern of a source function depends on the mechanical parameters of the rock massif, source geometry and rupture mechanism. Due to small epicentral distances the dimensions of the rock-burst focus should not be neglected.

It was expected that the time variable pattern of fracturing had a character of a non-linear dynamical processes. For the verification of this hypothesis the 39. rockburst records from the Ostrava coal basin (Nord Moravia), ranging the time interval Apr-Nov 1988 were subjected to the frequency- amplitude analysis. The treated series of recordings was selected of the large amount of seismograms of rockbursts from a given region, which were located in a small room. They were believed to represent one focal zone. The type analysis of the appurtenant seismograms confirmed that these quakes belonged to the same rockburst family; nine records of the treated series are shown in Fig. 6. The last rockburst of this series (4.10.1988) belonged to the strongest quakes of the studied sequence, its magnitude was M_1 = 1.73, see No. 37 in Fig. 6. The weakest tremor of the series was classified by magnitude M_1 = 0.25.

The results of the frequency analysis of the rockburst seismograms are in agreement with the non-linear principles of seismic energy radiation, c.f. the spectra given in Fig. 7, which belong to the seismograms from Fig. 6; here the amplitude maximum is denoted by the asteriks. It is well seen in the picture, that the spectrum maxima (except No. 37) always lie in the narrow frequency band 3.6 $\pm$ 0.5 Hz. As for the record No. 37, the maximum in its spectrum lies at 1.2 Hz, so that the third harmonics of this pulse is identical with the amplitude maxima of the previous pulses. By the other hand the wave period enlarged three times. This is in good agreement with the theory by

Poincaré/Mandelstham who formulated the possibility of enlarging the wave period n-times, where n is a natural number, for non-linear systems. Also the satelite local maxima are well developed in the spectra - some of them are denoted by black point. What also speaks in favour for non-linear processes in the rockburst foci.

5. SEISMIC DATA ANALYSIS

For testing possible non-linear processes in tectonical earthquake foci, a series of 6 recordings of aftershock events which followed the main 1989 Spitak earthquakes were analyzed. A relatively small number of suitable seismic events at our disposal was due to the principle that only those seismograms could be analyzed which were recorded right in the epicentre of the earthquake or in the near zone. The recordings from larger epicentral distances were not treated, since due to numerous reflections, dissipation and local effects, they considerably distort the information on the wave process in earthquake focus. For the same reason only shallow earthquakes were taken into consideration. (In principle also seismograms recorded in larger epicentral distances could be utilized if only proper signal filtration had been applied, which eliminated the above signal deformations).

In Figs 8 and 9 seismograms of six strong 1988/89 Spitak aftershocks are plotted which occurred in period Dec 19-31, 1988 (Fig. 8) and in Jan 4-8, 1989 (Fig. 9), respectively. (The main shock occurred on Dec 7, 1988). In Fig. 8 the horizontal components recorded in W-E direction are plotted in which the largest values of acceleration were recorded; the seismograms are complemented with the amplitude-frequency spectra.

In Figs 8 and 9 - from top to bottom - characteristic changes in seismogram forms are displayed. In this series the amplitude of accelerograms gradually increases in time. This increase corresponds to magnitude M_b increase, from M_b = 4.2, over M_b = 4.3 up to M_b = 4,9 (for Fig. 8). A similar series is given for Fig. 9 where M_b = 4.1, 4.4, and 4.8., respectively.

The changes in complexity of the wave form in both the 1988/89 Spitak aftershocks series, see Figs 8 and 9, can be considered as the transformation from linear to non/linear procesess. The spectra of these aftershocks change from complex and wide spectra which originally have numerous components in the high-frequency band (for lower M_b values) to modulated coherent spectra with the side satellite components (for the higher M_b values). This indicates that the process of automodulation due to increasing confining pressure has a more common character and under certain conditions can be found in both, laboratory and nature conditions. It is assumed that with increasing M_b values also the confining pressure growth when the same focal region is considered. This spectra evolution is demonstrated in Figs 10 and 11. It follows that a given structure can release the maximum elastic energy under full coherency of radiated pulses, what can be explained using the principles of non-linear dynamics.

The effect of coherency observed in the investigated aftershocks from Spitak series (1988/89) was also found in the case of the three aftershocks Oroville (1975, Aug 05, 06 and 11).

CONCLUSION

It is considered in the presented contribution, that the release of seismic energy can be characterised as a non-linear process. The main considered aspects of this approach were : non-linear superposition, represented by the amplitude modulation, the synchronisation, the coherency and a frequency shift of the resulting elastic radiation.

These aspects were found in the seismic records in wide frequency band : seismoacoustic signals (laboratory tests), records of local seismic network (rockbursts in coal mines) and seismograms of tectonical earthquakes. In all three these categories of measurement the symptoms of non-linearity of seismogenic process were detected and manifested: of wave-field modulation (satelites in spectra), synchronization (spectra simplification, their transformation to narrow spectral band), frequency shift to lower values (which does not result from enlarging the source size but from increasing degree of the process of non-linearity) and finally radiation coherency. Under this presumptions the seismic source can be characterised by a high degree of self-organizing and carry much higher energy (for a given volume) than this one derived on the basis of linear approach (the radiated energy is not proportional to the summ of elementary sub-sources, but to the square of this summ). On this basis also the disagreement between the source size observed in the nature and computed by means of linear physics, can be explained.

The non-linear approach can also be used as a new tool for the assessments of a maximum possibly released energy of the earthquake(at the moment of highest degree of radiated waves coherency) which is - for a focal/seismic zone - an important parameter for the seismic hazard classification.

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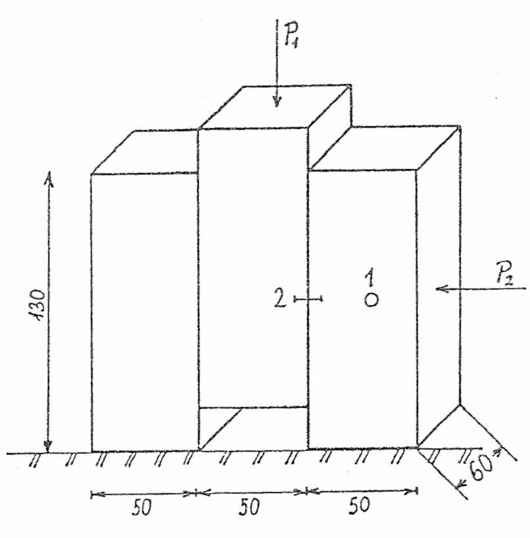

Fig. 1. Model set-up. Three magnesite blocks compressed by the confining force P_2; central block is pressed against the two outer blocks by load P_1.

1 - piezoelectric pick-up accelerometer,

2 - tensometer recording the displacement values. Model size is given in mm.

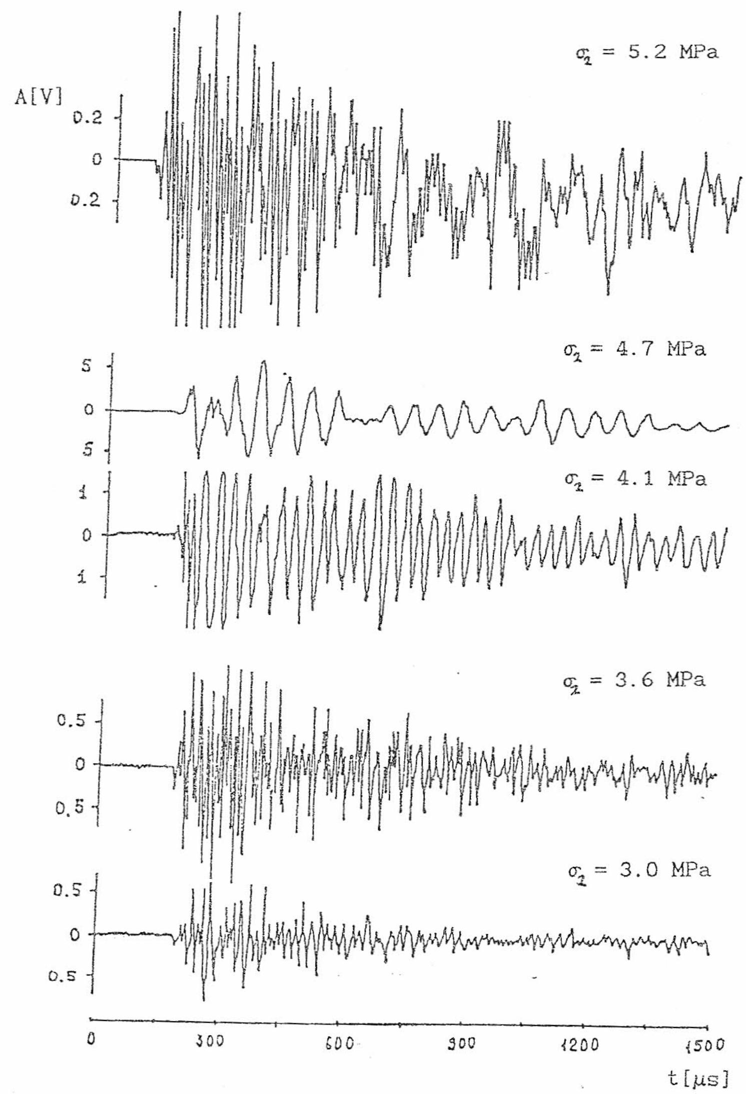

Fig. 2. Form of the stick-slip signals radiated in 5 different levels of confining pressure σ_2.
A - amplitude, t - time.

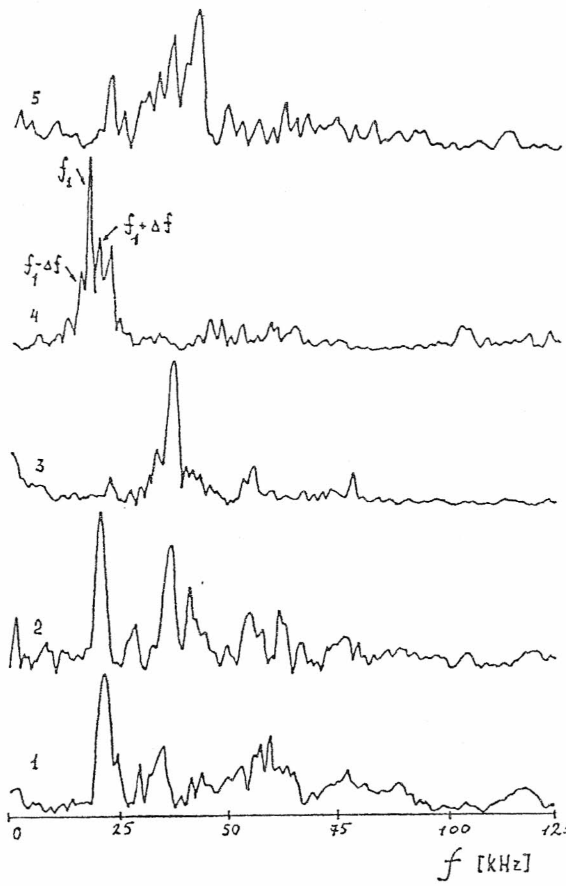

Fig. 3. Amplitude/frequency spectrum of the signals given in Fig. 2 . The spectra patterns are given in linear normalized scale. f_1 - maximum of the spectra in coherent stage of radiation.

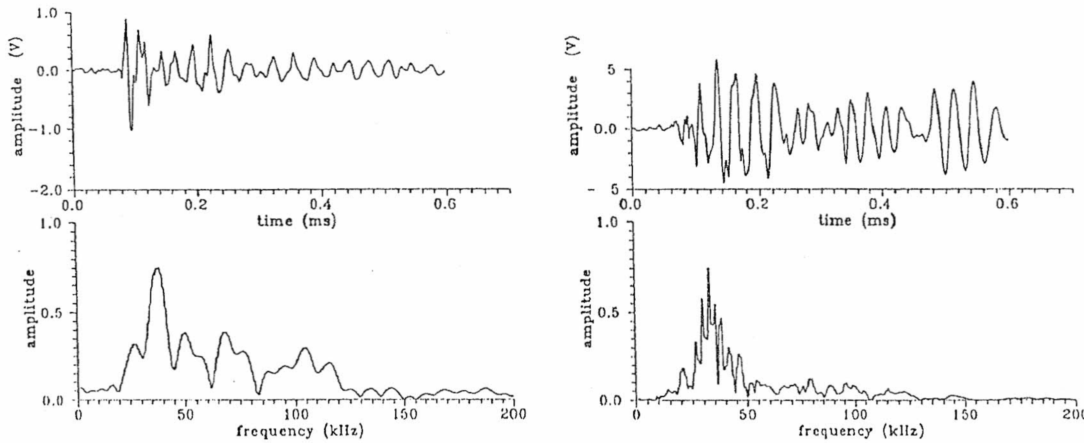

Fig. 4. Two seismoacoustic pulses from loaded magnesite model of a seismic source (upper part) and their amplitude spectra (lower part, rel. units).

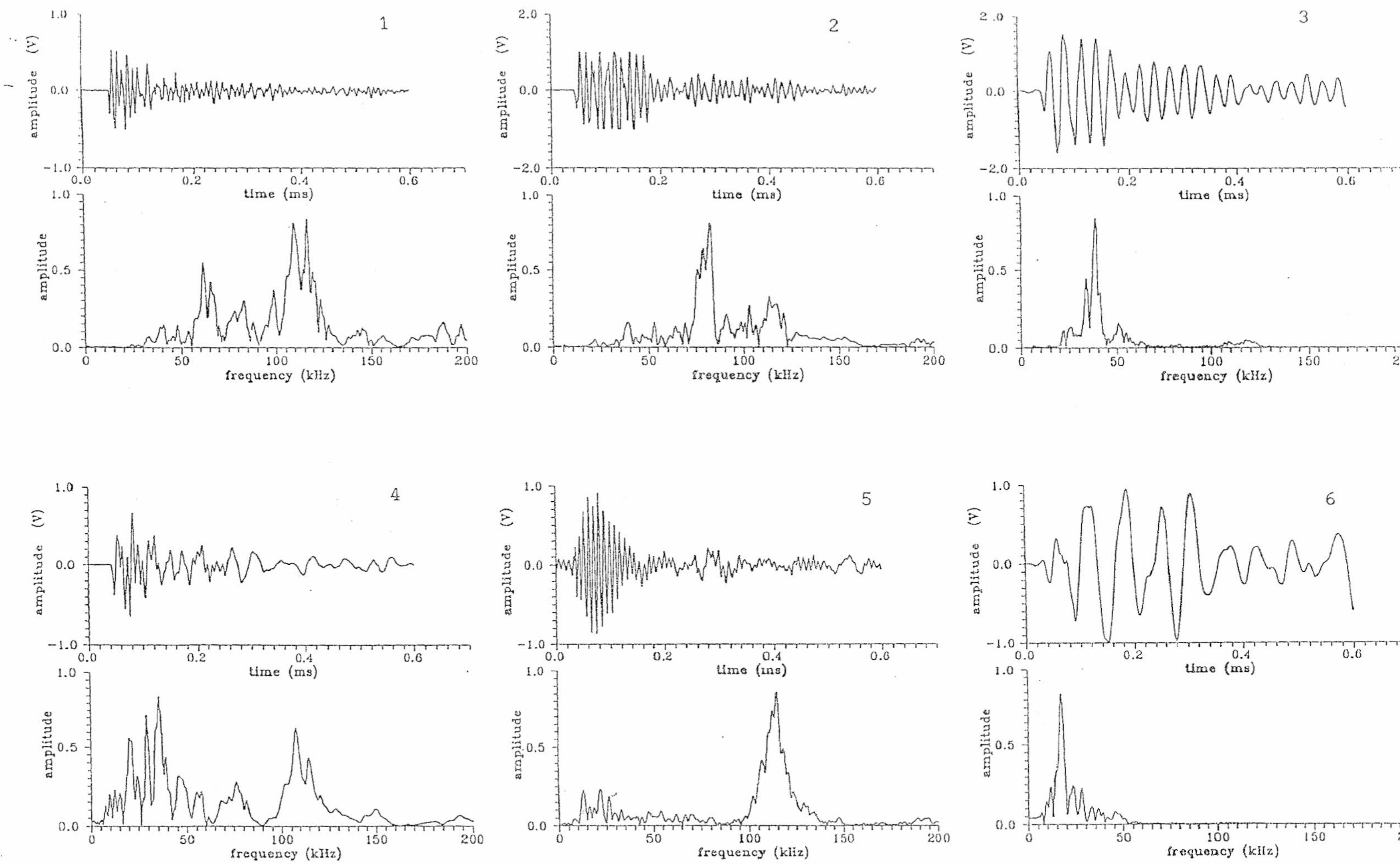

Fig. 5. Three acoustical pulses, 1, 2 and 3 from loaded fine grained sandstone soruce model and their amplitude spectra, see the row under the pulses 1-3. In the lower half of the figure three acoustical pulses 4, 5 and 6 from loaded coarse grained sandstone source model are shown together with their amplitude spectra (bottom row). Both the samples were taken from the Kladno coal region.

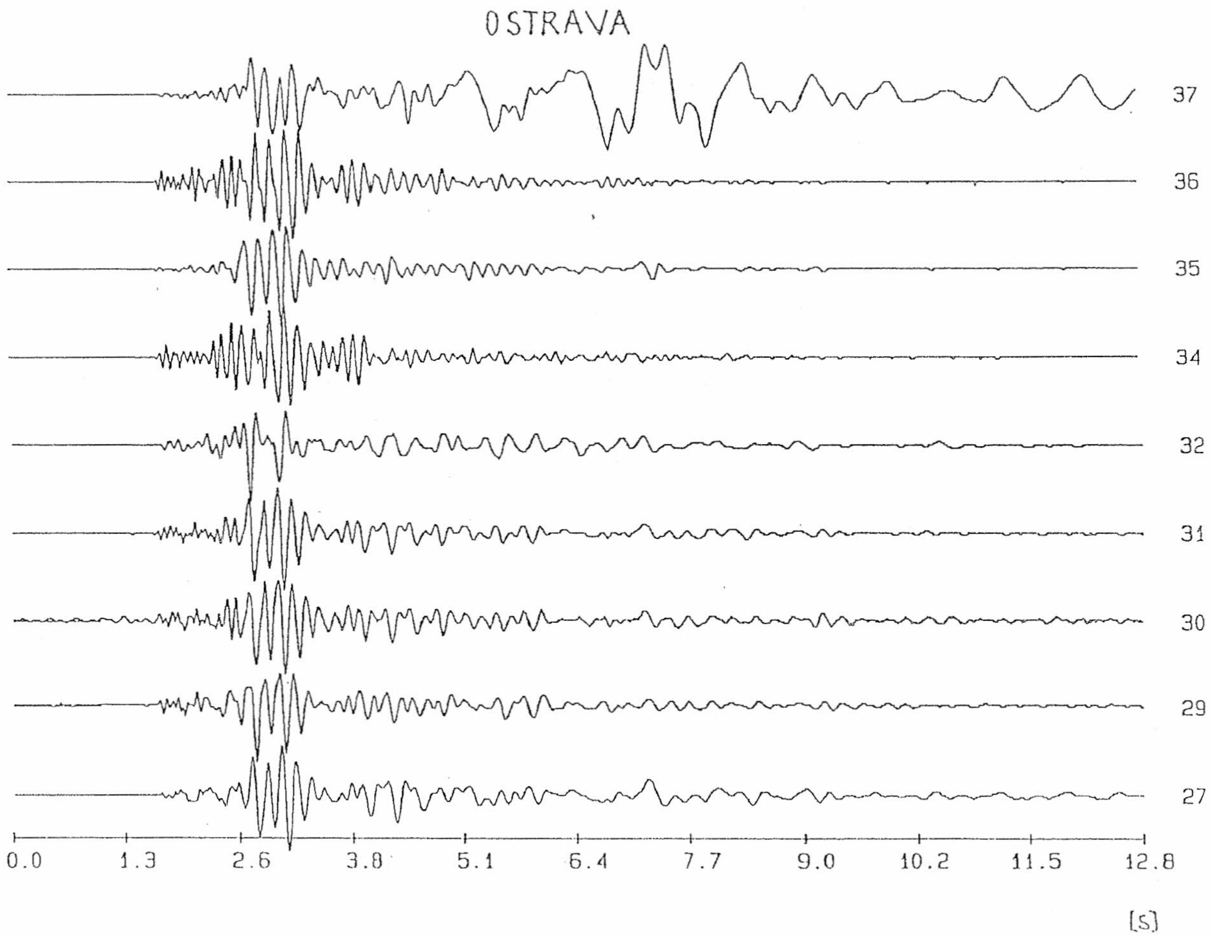

Fig. 6. Seismic records of nine rockburst events taken from the Ostrava coal region, which were selected from one locality in a time interval Apr-Nov 1988. Time is given in seconds, the amlitudes are normalized.

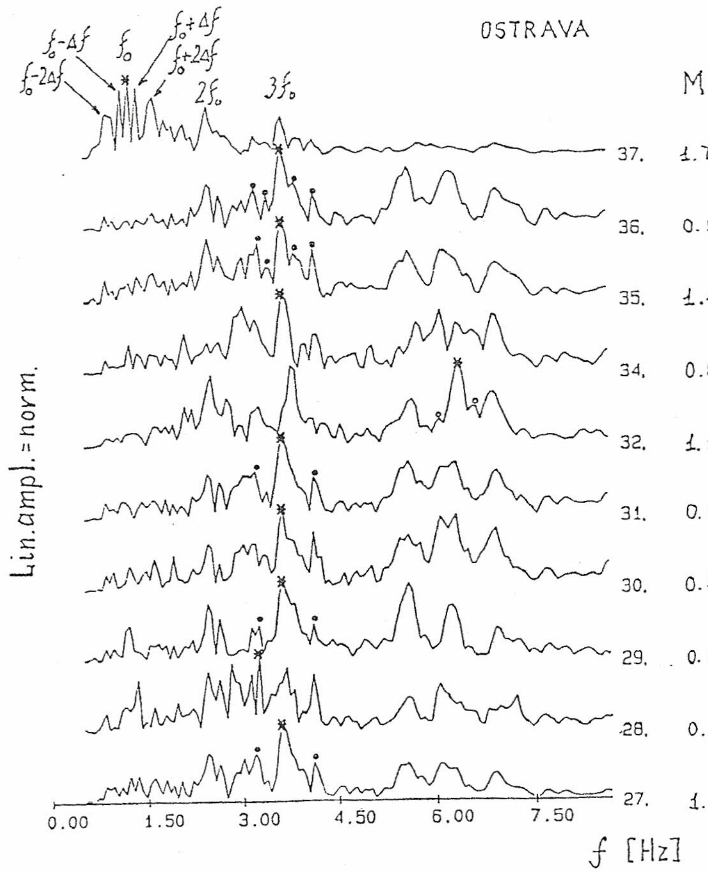

Fig. 7. Amplitude frequency spectra of the pulses from Fig. 6 in a lin/lin representation. By the asterisk the maximum values f_o in individual spectra are denoted, the point show the satelite local maxima $f_o \pm \Delta f_o$ or $f_o \pm \Delta 2f_o$.

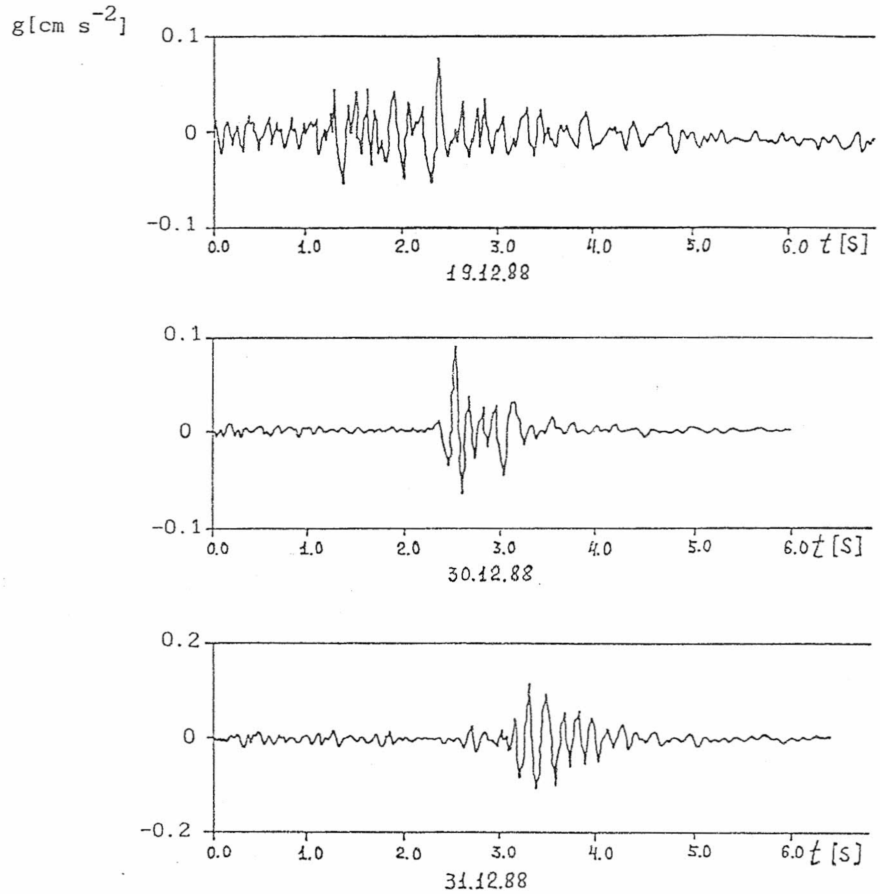

Fig.8. Three 1988 Spitak earthquake aftershocks, recorded by accelerometers, see the dates under seismograms, t - time, g - acceleration.

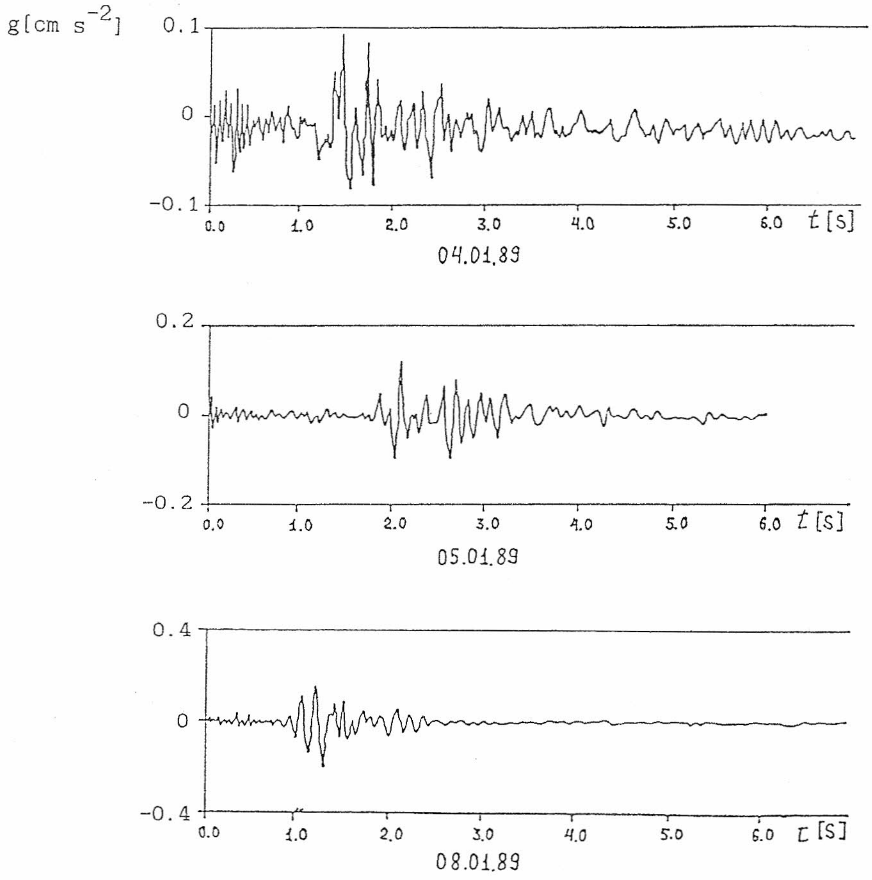

Fig.9. Three 1989 Spitak earthquake aftershocks recorded by accelerometers, see the date under seismograms. t - time, g - acceleration.

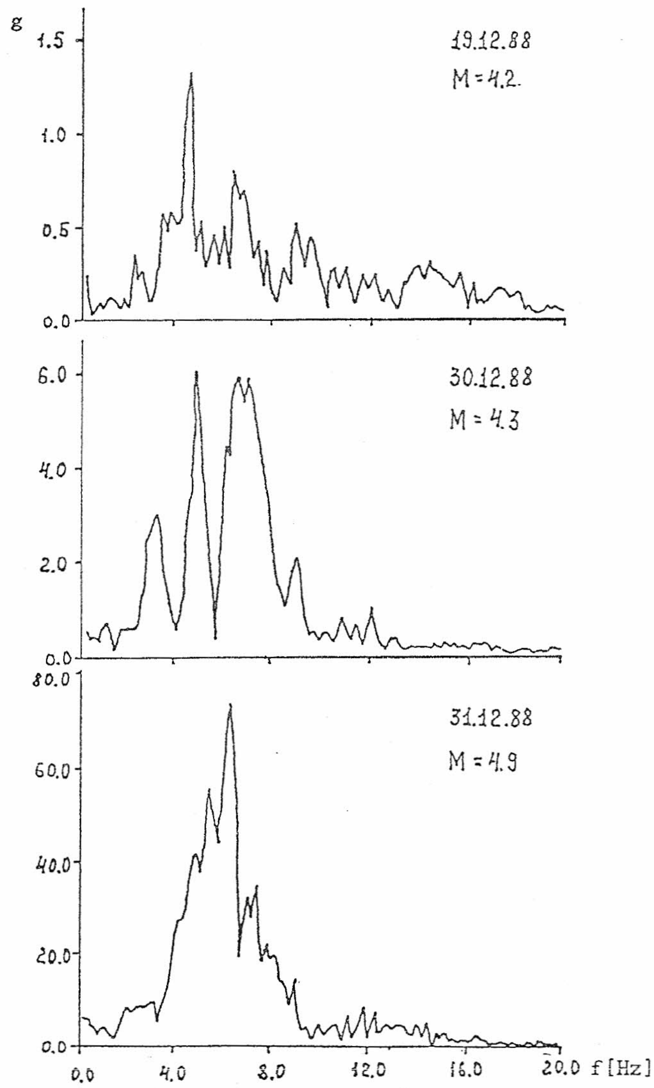

Fig.10. Frequency spectra (lin/lin) of the accelerograms in Fig. 8. f - frequency, g - acceleration.

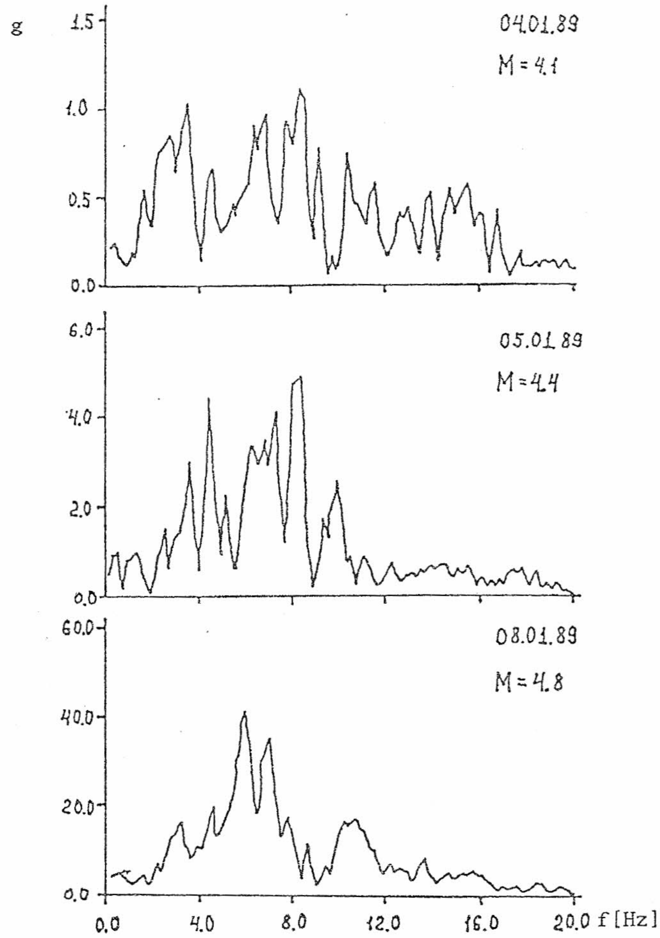

Fig. 11. Frequency spectra (lin/lin) of the accelerograms in Fig. 9. f - frequency, g - acceleration.