Chapter 12
Phase-Shifted Fields: Some Experimental Evidence

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Abstract We present a comparison between some experimental results on the interaction and synchronization of mechanical and electric fields; such a synchronization may appear with the phase delay by π/2, as shown in recent theoretical results. The solutions related to such a phase-shifted synchronization between some fields follow from the Asymmetric Continuum Theory. This theory concerns not only the mechanical fields, strains and rotations, but also other physical fields entering into interaction with stresses.

12.1 Introduction

Some experiments have brought a light on mechanisms that lead to synchronization between different dynamic processes under various kinds of applied loads and additional external impulses. We present some examples related to the interaction and synchronization processes between the deformations and applied loads with the accompanied mechanical and electric field impacts. Our consideration is based on both the new theoretical approach to the asymmetric continuum and on the experimental evidence of such a synchronization, as given in some papers.

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12.2 Synchronization and interaction: experimental evidence

Chelidze *et al*. (2006) presented the synchronization and triggering effects observed in samples subjected to a static basic load, close to a critical point (slip event experiments) and additionally to the weak mechanical or electric perturbations as an additional forcing.

These externally applied forces caused micro-slip episodes at the prepared surface, observed as acoustic emission bursts. The samples system consisted of two samples, stuck together with roughly polished neighboring surfaces; the gap between them was of microscopic size and the slips occurred on these stuck surfaces. The whole system serves as a simple model containing fracture zone or an active fault, at which repetitive episodes of slip take place.

The acoustic emission synchronized with applied oscillations:

a) of mechanical load
b) of externally applied voltage, but only in the case when the electric field direction was parallel to the gap between samples; perpendicularly applied electric field gave hampering effect on the slips

The experimental setup is described in Chelidze *et al*. this issue (Chapter 8, this issue). The acoustic emission (AE) and oscillating part of the externally applied forces were recorded using Sony Sound Forge software.

Further, we focus on the experimental series in which the electric field, parallel to the gap plane, acted as factor modifying response of the samples system to the static loads.

Most probably, acoustic emissions have originated in the gap zone. But it is obvious that processes in this zone were under control of the system of samples. Thus, some hidden structural adaptations of the samples to the experiment conditions permitted the observed repeated response to the stimuli. These adaptations should be of various scales, sub-molecular included. After an abrupt change of the conditions, the rise of the static part of externally applied electric field, the rhythm of acoustic emission changed immediately and then underwent some variations, in the time when a new pattern of repetitive acoustic bursts was gradually formed. In our opinion, such a result shows an adaptation of the samples to new condition.

Chelidze *et al*. (2006) state that synchronization limits the energy release at an individual event (burst). This was proven experimentally: “Sudden decrease or total cessation of synchronizing (electric) forcing is followed by acoustic burst of much larger energy than during periodic forcing”.

In the cited paper the authors observed the temporal evolution of phase difference between the maxima of acoustic emissions and external periodic forcing.

The applied electric field consisted of two components: the one oscillating from + 800V to –800V, and the constant one with initial constant voltage of 400V which has increased to 1900V in the middle of the experiment (about 28.6 s from the beginning). That is, it started to be bigger than the alternating field. This means that in the experiment’s first part, the voltage of external field oscillated between

+1200V and – 400V, and in the second part – between +2700V and +1100V. For these cases, the acoustic bursts were in different ways correlated to the oscillations of the external electric field.

In the first part of the experiment, the AE bursts coincided with all the extrema of the applied voltage; however, the entire burst started during the stage of the external field increase. We should be aware that in these experiments, both the stimulating impulses and the responses – acoustic emissions – did not oscillate in a sinusoidal way; the vertical scale in the reproduced display was a kind of decibel scale: the peaks were in fact more abrupt. Besides, a certain level of acoustic emission persisted in the considered experiments, obscuring beginnings and ends of the acoustic bursts. The response looks the same at "+" and "–" part of the stimulus curve; there is no visible hysteresis.

Further on, in the second part of the experiment with the increased static part of electric field, there occur changes in the rhythm of acoustic bursts. These changes, seen in Fig. 12.1, may be described as follows. The first very strong bursts consisting of two joint parts coincide with the nearest maxima of the oscillating field: one exactly, and the other with some phase shift, roughly $\pi/2$.

Subsequently, the AE bursts coinciding directly with the electric field maxima gradually decrease in time and finally there remains only an evident correlation of the bursts shifted in phase - by about $\pi/2$ - with the electric field maxima.

It is also worth to mention the observed synchronizations between the mechanical stimuli and the seismic noise, as described by Saltykov (2008); the observations, done in the region of Kamchatka and neighboring seas and islands, reveal the

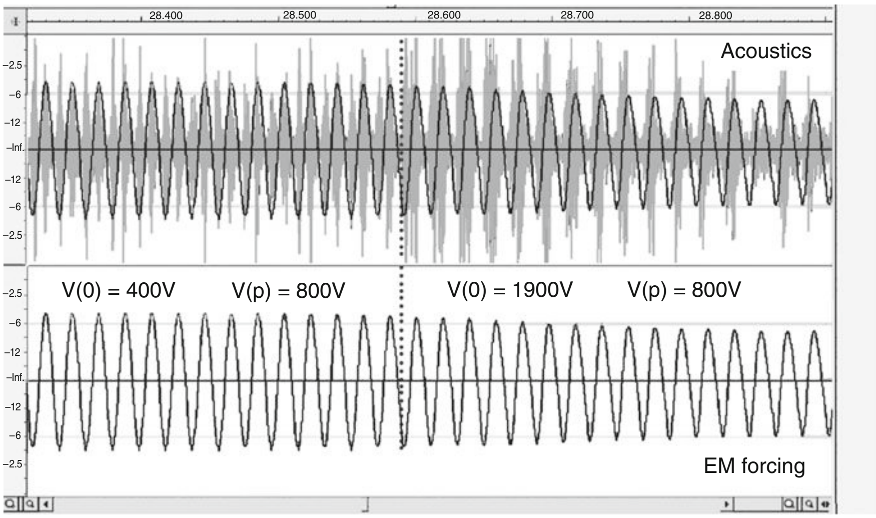

Fig. 12.1 Synchronization between the electric field oscillations and the acoustic bursts (after Chelidze et al., 2006 - modified); the curve of oscillating voltage V(p) is copied on the plot of acoustic emission (in grey), the vertical dotted line indicates a moment of increase of the static voltage

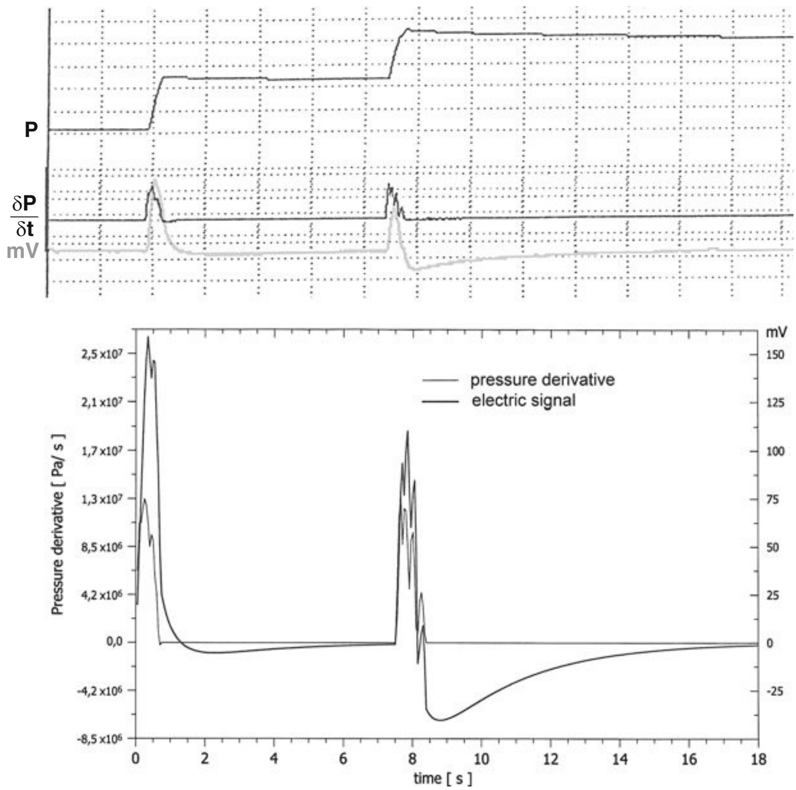

Fig.12.2 An example of correlation between the pressure applied to a limestone sample and excited electric polarization (upper part) and the numerical simulation results (lower part) (after Teisseyre, K.P., Hadjicontis, and Mavromatou, 2001)

synchronization of the envelope of high frequency microseismic noise to the Earth tidal O_1 waves. Such a synchronization appears before most of the large earthquakes in that area. Almost always, certain phase shift occurs – the envelope is delayed in relation to the Earth tides. This synchronization, of yet undisclosed mechanism, suits as an earthquake precursor in the region.

We should also note that Busse and Wang (1981) have found other interesting correlation effects; the two orthogonal acoustic waves shifted in phase by $\pi/2$, acting on a small disc (as compared to the acoustic wavelength) with its axis perpendicular to these waves produce a torque (acoustic torque). According to those authors, this effect is related probably to the particles of gas moving circularly over the disc (viscous effect rather than the Bernoulli pressure effect). This acoustic torque effect seems to present one more example of interactions of different fields.

Moreover, we analyze the experiments on anomalous piezoelectric effects conducted by V. Hadjicontis and C. Mavromatou (cf., Teisseyre et al., 2001) in which the appearance of electric polarizations was observed depending on the rate of load variations. For these experiments, the materials were chosen which do not show electric polarization under constant load, that means, which are non-piezoeletric in a common meaning. On other hand, the electric response of one of these materials, the limestone, to load is found to be doubly anomalous – once, because it depends on the load changes and, moreover, it shows a kind of some reversal of the produced electric signal, a rebound release effect revealed by the negative electric bays (see Fig. 12.2). In various numerical simulations conducted to reproduce the experimental results, the main rules were as follows: each increase in load causes an increment in the excited voltage, and this added part immediately starts to decline (its decay has taken many steps of simulation).

The shape of the decaying part of the electric response to mechanical stimuli suggests the concurrence of two or three relaxation phenomena, that is, one quick process and one or two slow ones.

12.3 Theoretical interpretation of co-action and synchronization effects

First, we will refer to the results of experiments done by Chelidze et al. (2006), as discussed above. A general conclusion is that acoustic response occurs when electric field variation, superimposed on the present conditions of externally applied electric fields and mechanical stresses, cause a break of material bonds, thus producing an acoustic emission. Episodes of acoustic emission cluster in the acoustic emission burst. The experimenters observed temporal evolution of the phase difference between the extrema of external electric field and the bursts of acoustic emission.

As mentioned above, two modes of synchronization between the stick-slip events (acoustic bursts) and the periodic electric field, *V(periodic)*, were observed.

First, the doubling synchronization (1:2): each electric extreme amplitude synchronized with acoustic bursts, this is the case when the applied direct *V(0)* voltage is smaller than the periodic voltage, $V(0) < V(periodic)$.

Second, the direct synchronization (1:1): the electric maxima synchronized with acoustic bursts; it appears when the applied direct*V(0)* voltage is greater than the periodic voltage $V(0) > V(periodic)$.

For $V(0) < V(periodic)$ the micro-fracture processes appear when the resulting field reaches maximum, that is, for the maxima of the periodic voltage. The fracture processes appearing at these maxima of the periodic electric impulses become immediately observed as the acoustic emission, the acoustic bursts, caused by the breaks of bonds and released rotation motions. Induced by this fragmentation, the series of single shear couples form the rotation couples where each of the two perpendicular couples has opposite shears (the case quite opposite to the case of shear double couple). Thus, the resulting shear field in this fragmentation process appears almost compensated to minimum.

For *V(0)* > *V(periodic)*,when a constant electric field is high enough, we can expect that each electric impulse can break the material bonds, but the process runs due to the applied external shears; we may notice that first we observe the broad acoustic peaks partly synchronized with the impulses and after some stabilization there remain more narrow bursts occurring with the $\pi/2$ phase shift, as the related slip process, released in a kind of slip avalanche, becomes delayed in time. Thus, at first we probably deal with both the rotation and slip rebound processes, while after stabilization only slip avalanche releases remain in sites where molecular bonds are already broken.

Thus, the most important for our consideration on interaction between the electric periodic impulses and micro-fractures is the fact that the acoustic emissions (waiting time series) are observed in both synchronization modes. This means that the synchronization modes are retarded in phase by $\pi/2$ (similarly as the results of the Hilbert transform); we can underline an organization role of the electric impulses on the response of the samples to the experimental conditions. This is an important result for us, to be compared with the theoretical part describing the interaction and synchronization processes in the Asymmetric Continuum Theory (Teisseyre, 2009).

Worth mentioning are also some other effects that may appear when studying various experimental results with the induced electric signals; we refer here to the experimental results obtained by Hadjicontis and Mavromatou (1994 and 1995; cf., Teisseyre K.P, et al., 2001). Among other things, Hadjicontis and Mavromatou (1994) have studied the transient electric signals appearing before the failure of limestone or other rock samples. The samples were subjected to a uniaxial compression; it was found that the emitted electric signals, attributed to stress-induced polarization in rock samples, follow the variations of the first time derivatives of load; this means, there is a correlation between the time derivatives of the pressure load and the emitted signals of electric polarization.

Such immediate correlations between the time derivatives of the applied pressure (corresponding to a sinusoidal pressure load shifted by $\pi/2$) and the electric signals, as obtained by Hadjicontis' group are presented here according to Teisseyre K.P., et al. (2001), in Figs. 12.2 and 12.3.

The presented examples of interaction and synchronization processes between the deformation and electric fields or between the acoustic waves and electric oscillations reveal synchronization with a phase shift of π/2; we intend to interpret this phenomena on the basis of the Asymmetric Continuum Theory (Teisseyre, 2009) and possible interaction processes included in it (Teisseyre, Chapter 3, in this issue).

Our theory explains the co-action and synchronization processes between the displacement and rotation motions or, in another form, between the strains and rotations; the phase shift of π/2 appears as a possible consequence of one of the forms of the related solutions. Such processes are naturally explained by the release and rebound co-action of these deformation fields.

Synchronization between the strain or acoustic oscillations and the electric field appears to be more difficult for interpretation. However, according to the Theory, the rotations can produce some anti-symmetric stress counterpart (stress moments)

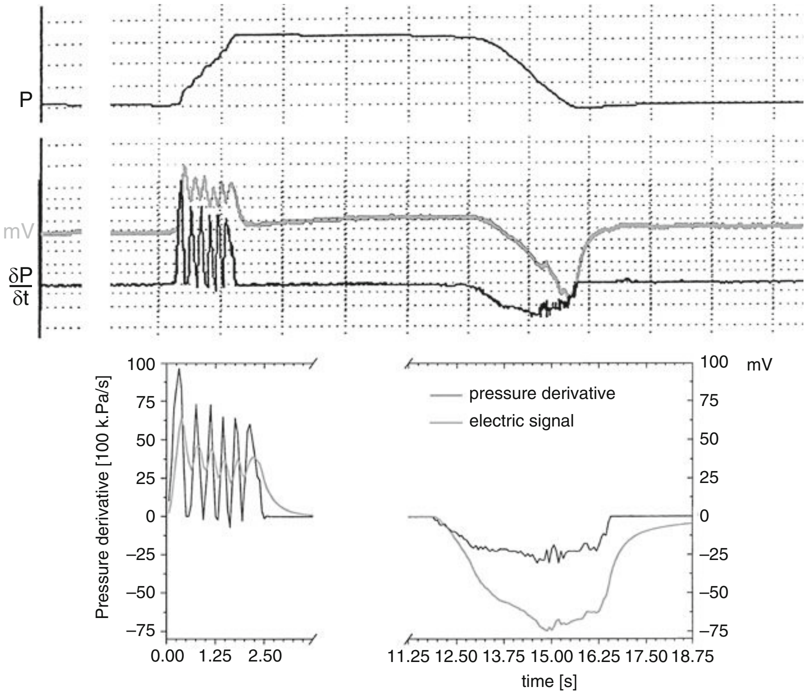

Fig. 12.3 Another example of correlation between the pressure applied to a limestone sample and excited electric polarization (upper part) and the numerical simulation results (lower part) (after Teisseyre, K.P., Hadjicontis, and Mavromatou, 2001)

and strains shifted in phase, as observed by the acoustic effects; such a chain follows from the synchronization of fields (cf., Teisseyre, Chapter 3, in this issue) and, further, can lead to the electric effects.

However, we can assume an intermediate action of the rotation field which can interfere and combine the strain or acoustic fields with an electric oscillation in more natural synchronization processes. In the proposed approach (cf., Teisseyre, Chapter 3, this issue) the electric and rotation fields can be directly synchronized under electric oscillations acting on rotations; the rotations will coerce strain or acoustic waves as is due to the appropriate synchronization solution. The reverse process is possible as well, and starts from strain impact, to be followed by rotations with a phase shift and an immediate electric response. The electromagnetic field stimulates rotation motions and acoustic emission; such a stimulation appears, among others, due to an increased mobility of the charge carriers. Therefore, the mechanical forcing and applied electromagnetic field lead to acoustic emission and spin motion. The latter releases the micro-displacements with the phase shift of $\pi/2$ and then the direct correspondence of phases appears after Hilbert transformation of the observed acoustic bursts.

12.3.1 Conclusions

We have presented a new interpretation of the synchronization processes with the shift of π/2. We have shown that in some experiments on the interaction and synchronization of the mechanical and electric fields there appears such a phase delay. In the very important experiments by Chelidze's group, these synchronizations appear in the plot shifted by the Hilbert transform to the waiting time series related to the acoustic emission. In the Theory presented in Chapter 3 (this issue), such a case corresponds to the expected phase shift between the synchronized spin and twist motions.

In searching for the interaction mechanism the interpretation we propose is such that the electric impacts cause the molecular bonds breaking and, at higher electric voltages, the rebound released micro-slips, which form an avalanche (triggering effect).

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