Triggering and synchronization of stick slip: Waiting times and frequency-energy distribution

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Received 23 June 2005; accepted 25 March 2006
Available online 28 July 2006

Abstract

Triggering and synchronization are encountered in many geophysical phenomena, including geodynamics. Both these effects are generated by the action of additional forcing, which is much smaller than the main driving force. That means that triggering and synchronization are connected with nonlinear interactions of objects, in this case with initiation of instability in systems that are close to the critical state. In seismic process the main component is the tectonic stress and the additional forcing is exerted by various external impacts like tides, reservoir exploitation, big explosions, magnetic storms, etc.

In the paper, the results of laboratory and field experiments on the electromagnetic (EM) initiation and synchronization of mechanical instability (slip) are presented. Slip events were recorded as acoustic emission bursts. In the first series of experiments strong EM pulses were applied to the mechanical system driven close to the critical state, namely, to the (dry) rock samples placed on an inclined supporting sample at the slope angle less than, but close to the critical slip angle. It has been found that EM impact initiates slip with probability \( P \approx 0.07 \) at the voltage \( \Delta V = 1.3 \text{ kV} \) and with probability \( P \approx 0.2 \) at \( \Delta V \approx 10 \text{ kV} \) if the EM field is applied parallel to the slip surface (first mode). On the other hand, the application of EM pulse hampers the slip considerably if the EM field is directed perpendicularly to the slip surface (second mode): the slip was not observed even at the angle that was larger than the critical one.

In the second series of experiments the periodic EM and mechanical forcing were applied to the standard slider-spring system. It was discovered that periodic EM force of frequency \( f \) superimposed on the constant driving force excites periodic microslips of rock samples with double frequency \( 2f \). Combined impact of periodic and constant voltages invokes transition from double frequency synchronization to \( 1:1 \) synchronization if the direct component of voltage is larger than the periodic one. Synchronization affects not only waiting times, but also frequency-energy distribution: i. the energy of bursts emitted in synchronized mode have much less scatter than in the absence of the periodic forcing, ii. the sudden decrease of synchronizing forcing is followed by acoustic burst of much larger energy than during forcing.

The elementary theory of EM triggering and synchronization is given: the effects are explained by the action of EM ponderomotive (electrostriction) forces, which modify Coulomb stress similar to the well known pore pressure model. The formalism of transition from \( 1:2 \) to \( 1:1 \) synchronization is considered.

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Keywords: Triggering; Phase synchronization; Stick-slip; Electrostriction; Seismicity

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0040-1951/ - see front matter © 2006 Elsevier B.V. All rights reserved.
doi:10.1016/j.tecto.2006.03.031
1. Introduction

Triggering and synchronization are the two faces of the same coin; both effects imply that the additional forcing causing triggering and synchronization is much smaller than the main driving force, which means that these phenomena are connected with nonlinear interactions of objects, namely with initiation of instability in systems that are close to the critical state. In seismic process the main component is the tectonic stress and the additional forcing is exerted by various external impacts: tides, reservoir exploitation, big explosions, magnetic storms, etc. Up to now the problem is far from being resolved and relevant publications are controversial due to the complexity of natural processes (Beeler and Lockner, 2003; Scholz, 2003a; Grasso, 1992; Nikolaev, 1994; Scholz, 2003b). Understanding of main regularities can be obtained in controllable experiments. We carried out laboratory experiments on the slider-spring system with superimposed pulse or periodic electromagnetic (EM) forcing, which is weak in comparison with the main dragging force of the spring. The use of EM impact was prompted by experiments carried out in 1983–1988 by the Institute of High Temperatures of Russian Academy of Sciences (IHT RAS) in the Central Asia, at the Bishkek test area. After performing series of MHD soundings as well as “cold” discharges, initially aimed to finding resistivity precursors of strong earthquakes in the upper layers of Earth crust, an unexpected effect of microseismicity activation by strong EM pulses has been discovered (Tarasov et al., 1999). We reproduced the effect in laboratory conditions and it turns out that EM forcing is a flexible tool for the study of triggering and synchronization phenomena in laboratory slider experiments (Chelidze et al., 2002; Chelidze and Lursmanashvili, 2003; Chelidze and Matcharashvili, 2003; Chelidze et al., 2005).

2. Experiments

2.1. Triggering experiments

The main objective of experiments was to find out whether EM pulse could indeed displace the rock sample, resting on the supporting sample at the slope of support, less than but close to the critical slip angle. The details of experiments are presented in Chelidze et al. (2002).

The system consists of two pieces of rock; the upper piece can slip on the fixed supporting sample if a special frame tilts the latter one up to the critical angle $\alpha_c$. Electrodes were applied in the following ways: i. to the bottom of the supporting sample in a coplanar manner or to the sides of the supporting sample (the first mode); ii. to the upper surface of the sliding sample and the bottom of the supporting one (the second mode). In the first case the EM field is oriented roughly parallel to the slip surface and in the last case current lines are normal to it.

Slip event was registered as acoustic bursts by the sound card of PC.

In the most cases the supporting and the slipping blocks were prepared from basalt; these samples were saw-cut and roughly finished. Other samples such as granite, labradorite, and glass, which were better finished, were also tested. The height of surface protuberances was in the range 0.1–0.2 mm for basalt samples and 0.05–0.1 mm for the other ones. The basalt samples were preferred because they do not contain significant quantity of piezoelectric minerals.

For assessment of mechanical equivalent of electrical impact both direct and theoretical methods were used. In the first case the mechanical force, initiating slip at the same angle $\alpha < \alpha_c$, that has been set in experiments with EM-impact, was measured by dynamosimeters: the force, equivalent to slip-initiating EM-impact was found to be of order of 0.2 N. Another way to get mechanical equivalent is to calculate it from the general equation of balance of forces for a block placed on the inclined plane and in this case the same order of mechanical equivalent was obtained (Chelidze et al., 2002).

2.2. Synchronization experiments

Experimental set up in synchronization experiments represents a system of two horizontally oriented plates of roughly finished basalt. A constant pulling force $F_p$ of the order of 10 N was applied to the upper (sliding) plate; in addition, the same plate was subjected to periodic mechanical or electric (50 Hz) perturbations with variable amplitude (from 0 to 1000 V), which was much weaker (of order of 1 N) compared to the pulling force; the electric field was normal to the sliding plane. Acoustic bursts accompanying slip events were registered by the sound card of PC. Details of the setup and technique are given in Chelidze and Lursmanashvili (2003).

3. Results

3.1. Triggering

We found that the application of EM pulses (1300 V) in the first mode, i.e. to the coplanar electrodes at the
Fig. 1. a, b. Acoustic emission (AE) during EM triggering of slip (labradorite sample). a — the whole recording; b — the part of recording with expanded time axis. Stiff spring ($K_s = 1000 \text{ N/m}$), pulling force $F_p = 3.5 \text{ N}$, normal (nominal) stress $\sigma_n = 2 \text{ kPa}$. The y-axis in all figures shows amplitude in dB. Upper trace shows acoustic emission during slip, lower trace records the superimposed EM excitation. Here and in Figs. 2–4, 6, 9) the time (abscissa) axis the first two positions correspond to hours, next two to minutes and the last numbers are for seconds and milliseconds passed from the beginning of experiment.
bottom of support, initiates slip in approximately 40 cases from 600 runs (i.e. the slip initiation probability is around 0.07) either during pulse (i.e. in the active phase), or after it (i.e. in the passive phase). The last observation means that the polarization of the samples can be important for the slip initiation. The typical recording of acoustic emission generated by the slip event is shown in Fig. 1a and b for different time scales.

The probability of slip triggering rises to 0.2 when the applied voltage was increased to 10 kV.

Not a single slip event has been registered in the second mode (300 tests), when the applied electrical field was oriented in the direction of the normal to the slip surface, even at a repose angle larger than the critical one. That means that in the second mode EM field hampers slip.

![Acoustic channel](image1)

![Electric channel (no forcing)](image2)

**Fig. 2.** a, b. Typical acoustic emission during slip without periodical impact: a — random release of acoustic bursts. The stiffness of spring $K_s = 1000$ N/m; $\sigma_n = 2$ kPa.; the mean drag velocity $v_d = 2.5$ mm/s; dragging force $F_d = 3.5$ N; $T = 20$ °C; humidity $W = 40$%; b — quasiperiodic acoustic bursts (without external periodical forcing) with the mean waiting time 0.7 s during natural slip; experiment with a soft spring; $v_d = 1.45$ mm/s; $F_d = 3$ N; $K_s = 125$ N/m; $T = 20$ °C; $W = 50$%. Here and in (Figs. 3, 4, 6, 9) the amplitude of AE and synchronizing field is given in dB.
3.2. Synchronization

In our experiments the following parameters were varied: i) the stiffness of the spring, $K_s$; ii) the frequency, $f$, of superimposed periodical perturbation; iii) the amplitude of the excitation (applied voltage $V_a$); iv) the direction of applied electrical field; v) the velocity of drag, $v_d$; vi) the normal (nominal) stress $\sigma_n$.

The typical background behaviour of the system during conventional stick-slips is presented in Fig. 2a,b. It is evident that in these conditions AE events do not manifest any visible periodicity at the time scale from several to hundred milliseconds.

The slip process, affected by the additional weak (0.1–0.5 N) mechanical periodic force is shown in Fig. 3. The upper trace corresponds to AE signals generated by elementary slip events and the lower one to the superimposed periodic mechanical perturbation.

We see that the periodic perturbation imposes on the slip a clear periodicity in slip-generated AE packages: acoustic events, generated by elementary slip occur once per period of mechanical forcing. The maxima of AE packages (approximately) coincide with the maxima of the perturbing force.

Slip with superimposed periodic low-frequency EM field ($f \approx 60$ Hz) of varying intensity, oriented normally to the slip surface is presented on Fig. 4a,b,c. The significant synchronization at this frequency occurs at $V_a \geq 500$ V. Under EM excitation the AE events (microslips) occur twice per period (Fig. 4c). The maxima of AE coincide (approximately) with the extreme points of oscillation. Synchronization was observed only at some definite values of set of parameters ($K_s, f, V_a$). The “phase diagram” for variables $f$, $V_a$, or so-called Arnold’s tongue (see Pikovsky et al., 2003) is presented on Fig. 5.

It should be noted that the phenomenon of synchronization was observed only with the EM field directed normally to the slip surface. When the EM field was applied to the vertical sides of the slipping block, that is, roughly parallel to the slip plane, we were not able to observe the effect of synchronization. We conclude that the synchronization is related to “electromagnetic braking” of slip at passing the extreme values of sinusoidal EM forcing and a sudden slip after accumulation of enough stress provided by spring pull.

Moistening of the slip surface by wetted blotting paper does not affect the “mechanical” synchronization, but practically kills the “electromagnetic” synchronization.

We observe transition (bifurcation) in stick-slip from 1:2 or period doubling synchronization, when two slip events occur per a period of EM forcing, to 1:1 synchronization, when one slip event occurs per a period of forcing (Fig. 6) at simultaneous action of direct $V(0)$ and periodic $V(p)$ voltages; transition occurs at $V(0) > V(p)$.

Synchronization affects not only waiting times, but also frequency-energy distribution: the amplitudes of bursts are much less scattered than that in the absence

![Fig. 3. Control of slip process by a weak (0.1–0.5 N) periodic mechanical impact. Upper trace — acoustic emission during slip, lower trace — periodic impact, $f=50$ Hz. Stiff spring ($K_s=1000$ N/m), $F_p=8.5$ N, $\sigma_n=2$ kPa. Weak perturbation was applied simultaneously with pull. Synchronization appears 4.2 s after beginning of experiment.](image-url)
of periodic forcing. The energy released by acoustic pulse was calculated as the area, confined by the acoustic wave record. We tried to plot (Fig. 7) the distribution of the number of AE events versus reduced power of AE (that is analogue of Gutenberg–Richter plot) in sequential windows (time intervals) using data of experiment with a different intensity of forcing (Fig. 4a). The (negative) slope of the plot is maximal in the most synchronized part of AE record (Fig. 4), due to the increasing contribution from small events leading to the appearance of plateau in the small energy section and decreasing the number of strong events (Fig. 11 in Chelidze et al., 2005). That means that the energy is pumped from large events to some intermediate scale. As the contribution from very large events is limited, the plot in this interval looks like magnitude-frequency distribution for characteristic earthquake model; hence the distribution of energies becomes less scattered due to increase of the share of “characteristic” events.

Fig. 4. (a) Acoustic emission during slip under variable from 0 to 1000 V external periodical voltage. b — the extended part of record with zero EM forcing; c — the extended middle part of record under maximal EM forcing. Note complete phase synchronization — PS.
Fig. 5. Stick-slip synchronization area (Arnold’s tongue) for various intensities ($V_a$) and frequencies ($f$) of the external forcing. Filled circles correspond to the perfect synchronization and empty ones correspond to the absence of synchronization. Circles with crosses mark the areas of intermittent synchronization.

Fig. 6. Transition (bifurcation) in stick-slip from 1:2 synchronization (period doubling) to 1:1 synchronization at simultaneous action of direct $V(0)$ and periodic $V(p)$ voltages; transition occur at $V(0) > V(p)$. 
Decrease of contribution of extreme events at synchronization is confirmed by calculation of the coefficient of variation $CV$ ($CV = \text{standard deviation} / \text{mean}$). As it is shown in Fig. 8, the extent of the deviation from the mean value of released AE power calculated for consecutive sliding windows, decreases at synchronization. That means that synchronization limits the energy release associated with individual events (quantization effect). Sudden decrease or total cessation of synchronizing forcing is followed by acoustic burst of much larger energy than during periodic forcing (Fig. 9a,b).

4. Physical mechanism of electromagnetic control of slip

In order to understand physics of EM triggering and synchronization it is necessary to consider fundamentals of surface phenomena. The majority of intermolecular and intersurface forces, responsible for adhesion and friction are of electromagnetic origin, which means that in principle the external electrical field can affect the intersurface adhesion (friction) forces and thus initiate slip on the inclined plane or synchronize slip events in slider-spring system. All surface forces, acting simultaneously, result in some total adhesion (friction) force $F_f$:

$$F_f = \mu F_n;$$

where $\mu$ is the friction coefficient and $F_n$ is the normal component of force acting on the body (gravity, compression).

The elementary theoretical model of EM coupling with friction can be formulated in the following way. It
is well known that an application of EM field to the
dielectric invokes some forces acting upon molecules of
the body; the resultant of them is called the ponder-
omotive (electrostriction) force $F_p$ that affects the whole
sample. The force is proportional to the gradient of the
field intensity squared and it carries away the sample in
the direction of the largest intensity. The electricstriction
tensor $T_n$ operating on the element of dielectric’s
surface in EM field of intensity $E$ under the assumption
that the sample of dielectric constant $\varepsilon$ is surrounded by
the immobile dielectric medium in $ESU$ system is
(Tamm, 1966):

$$T_{np} = \frac{\varepsilon + (\partial \varepsilon/\partial \delta)\delta}{8\pi} E^2 n,$$

or

$$T_{nn} = -\frac{\varepsilon - (\partial \varepsilon/\partial \delta)\delta}{8\pi} E^2 n,$$

Fig. 9. Increased acoustic energy release after decreasing (a) or total cessation (b) of periodic forcing, which means that synchronization limits the
energy release associated with individual events (quantization effect).

$$\text{Acoustics}$$

$$\text{Variable EM forcing}$$

$$\text{Acoustics}$$

$$\text{EM forcing}$$

$$\text{EM forcing switched off}$$

here $T_{np}$ is electrostriction tensor, when the field $E$ is
parallel to the external normal $n$ to the considered
surface element and $T_{nn}$ is the same for the case when the field $E$ is normal to $n$.

We can imagine that the elastic strings are stretched along the field lines: in our case according to relation (3) they build the side thrust on each other in the first mode and pull together the surfaces of sliding and supporting samples according to relation (4) in the second mode.

The above equations can be simplified if the dielectric increment due to the electrostriction force is negligible: $(\partial \varepsilon / \partial \delta \rightarrow 0)$. Taking into account also that:

(a) the samples were not ideally finished and there were some air-filled gaps between them in the contact area;

(b) the resistivity of basalt samples at room humidity is in the range of $10^4 - 10^6 \ \Omega \cdot m$ and the resistivity of air is much larger, of the order of $10^{16} \ \Omega \cdot m$, we conclude that the major part of the voltage drop occurs in the gap.

Introducing some effective value of opening $d_{\text{eff}}$ and applying Eqs. (3) and (4) to the gap space we obtain for the ponderomotive force $F_{pi}$ acting on the gap surfaces the formula:

$$F_{pi} = \pm \frac{\varepsilon_{\text{eff}} S}{8\pi} \left( \frac{\Delta V_{\text{eff}}}{d_{\text{eff}}} \right)^2 n,$$

where $\Delta V_{\text{eff}} / d_{\text{eff}}$ is the effective voltage gradient in the gap and $\varepsilon_{\text{eff}}$ is the effective dielectric constant of the gap which is between values of $\varepsilon$ for the air and the sample: $1 < \varepsilon < 5$.

Assuming $\varepsilon_{\text{eff}} = 2.5$, $S = 100 \ \text{cm}^2$, we have to put in Eq. (7) the gradient $(\Delta V_{\text{eff}} / d_{\text{eff}}) = 0.07 \ \text{V/cm}$ in order to obtain the experimental values of slip-initiating ponderomotive force, namely, $F_p \approx 0.2 \ \text{N}$. The above value of $F_{pi}$ can be considered as an order of magnitude of ponderomotive force that promotes the slip in the first mode and hampers it in the second mode, according to the expression (5) for the accepted set of parameters.

Thus, expression (2) can be rewritten in terms of stresses, taking into account (5):

$$\tau = \mu(\sigma_n \pm \sigma_{\text{es}})$$

where $\tau$ and $\sigma_n$ are correspondingly shear and normal stress; $\sigma_{\text{es}}$ is the reduced value of electrostriction component of stress, $\sigma_{\text{es}} = F_{pi} / S$. Eqs. (5) and (6) can be generalized to include the case of alternative/periodic EM field. If the state of the slider-spring system is close to critical, the nonlinearity of friction process allows for synchronization of slip events by periodic EM forcing, that is by the electrostriction component $\sigma_{\text{es}}$ (see also Section 6).

It is evident that Eq. (6) is similar to the well known expression for the friction force with a pore pressure term: $\tau = \mu(\sigma_n \pm P_f)$, where $P_f$ is pore pressure (Sibson, 1994).

5. Synchronisation: quantitative analysis

The tools for quantitative analysis of the strength of synchronization were tested on the recording of stick-slip process, where the superimposed periodic EM field intensity was raised monotonously from 0 to 1000 V and then decreased in the same way to zero (Fig. 4). Depending on the amplitude of synchronizing force the regimes of slip recorded as acoustic emission vary from the perfect phase synchronization of slip events with the perturbing periodic EM impact, to the complete desynchronization of microslip events and perturbations.

Before we proceed to the quantitative synchronization analysis, the recordings were inspected visually. For example, visual inspection of Figs. 4 and 6 reveals clear coincidence of external sinusoidal cycles and AE bursts. Qualitatively this points to synchronization.

Fig. 10. Time series of time intervals between consecutive maximal amplitudes of acoustic signals (waiting times) in consecutive $\pi$-periods of external forcing (compare with Fig. 4).
In order to assess synchronization in the qualitative manner we used the easiest approach for estimating phases of acoustic signal: digitized waveforms were transformed to sharp spikes to have well pronounced markers. Then time series (catalogues) of time intervals between consecutive maximums (waiting times) \((Δt=t_i−t_{i−1})\) in wave trains for \(\pi\) periods of external sinusoid (Fig. 10) were composed (time scale in Figs. 10–14 corresponds to sequential values of \(t_i\)). Besides, catalogue of power of acoustic emission events was compiled; the power was calculated as the plot area delineated by a singled acoustic burst recording.

After all, because our dataset was transformed to a spike train, containing distinct markers, we used phase difference determination technique described in Pikovsky et al. (2003). Additionally, in order to achieve more reliable phase construction and precise synchronization testing, the instantaneous phase of real acoustic signal was defined employing analytic signal concept, based on the Hilbert transform (Pikovsky et al., 2003). Both approaches yield similar results. For the same reason of getting quantitative measures of synchronization, the mean effective phase diffusion coefficient \(D = \frac{1}{N} \left[ \langle (Δφ^2) \rangle - \langle Δφ \rangle^2 \right] \) and the probability density distribution of waiting times have been also calculated. In order to have additional quantitative tests for phase synchronization the Shannon entropy \(S = -\sum_{i=1}^{N} P_i \log(P_i)\), where \(P_i\) is the probability of event to occur within the \(i\)-th box was calculated for the mentioned phase difference sequence; the calculation of \(S\) shows the level of ordering in the synchronized complex dynamics (Cover and Thomas, 1991).

All mentioned methods were applied to the experimental data (Fig. 4) obtained under variable intensity of forcing; the results are shown in Figs. 10–14, and 7, 8.

In Fig. 11 we present the temporal evolution of phase difference \(Δφ\) obtained from Hilbert transform of waiting times time series. Well-defined horizontal part of synchrogram (Fig. 11) represents the time, during which the acoustic emission becomes phase synchronized to the external sinusoidal influence in the wide range of their amplitudes (from approximately 500 V to

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![Fig. 11](image)

Fig. 11. Phase differences \(Δφ\) between the whole sequence of maximums of acoustic emissions’ bursts (AE catalogue) and external sinusoidal signal.

![Fig. 12](image)

Fig. 12. Variation of the full width of probability density distribution of phase differences between the catalogue of acoustic events and periodic signal at a half maximum (FWHM), calculated for consecutive sliding windows, containing 500 events.
1000 V). Clear phase synchronization becomes especially obvious, as long as in the most synchronized part of plot phase difference variation $\Delta \phi$ does not exceed 10 rad (compare with the total $\Delta \phi$ increment of 1800 rad during whole experiment).

It is known that the probability density distribution must be narrower for the synchronized signal compared to a non-synchronized one. As it follows from Fig. 12, the full width at half maximum (FWHM) of probability density distribution of phase differences between AE pulses and sinusoidal forcing is indeed much narrower for the synchronized part of Fig. 4. Frequency locking, expressed as a minimum of the phase diffusion coefficient is also a quantitative measure of the phase synchronization (see Fig. 13).

Moreover, clear decrease of Shannon entropy value $S$ indicates that dynamics of acoustic emission becomes much more regular in the synchronized part of acoustic emission data set (Fig. 14).

We hope that the methods applied in the present work to the laboratory data can be used in the future for detection and quantitative assessment of seismic process synchronization by a weak external impact.

6. Synchronisation: physical mechanism

It is well known that the slider-spring system displays the stick-slip behaviour described by the nonlinear equations (Dieterich, 1979; Ruina, 1983; Becker, 2000):

$$\tau = \sigma_n \left[ \mu_0 + \Theta + A \ln \left( \frac{v_d}{v_c} \right) \right] ; \quad \dot{\Theta} = \left( - \frac{v_d}{d_c} \right) \left( \Theta + B \ln \left( \frac{v_d}{v_0} \right) \right) ,$$

where $\tau$ is friction stress, $\sigma_n$ is normal stress, $\Theta$ is the surface state parameter, $\mu_0$ is a nominal (constant) value of friction, $d_c$ is the dimension of asperity, $v_d$ is slip speed, $v_0$ is the initial value of $v_d$ and $A$ and $B$ are constants. Both theoretical solutions and experiments demonstrate possibility of very different behaviour of the system depending on the conditions of the test. For example, nonlinear analysis of a simple quasistatic slider-spring system with rate and state dependent friction shows chaotic dynamics behaviour in the deterministic sense (Becker, 2000). It particularly, at the critical value of spring stiffness the friction stress may undergo oscillations close to periodical.

On the other hand, it has been shown (Ott et al., 1990; Bocaletti et al., 2000) that it is possible to control the behaviour of chaotic systems using very small feedback impact. The matter is that the attractor of a chaotic

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Fig. 13. Variation of phase diffusion coefficient $D$ of phase differences, calculated for consecutive sliding windows, containing 500 events.

Fig. 14. Variation of Shannon entropy $S$ of phase differences, calculated for consecutive sliding windows, containing 500 events.
system contains an infinite number of unstable periodic orbits. Given such attractor, one can choose some of the low-period orbits (or steady states) embedded in the attractor and use a feedback perturbation of an accessible parameter $P$ of the system in order to stabilize the chosen orbit and thus improve the performance of the system, for example, convert the chaotic behaviour into periodic process. The extreme sensitivity of chaotic systems to external impact allows control of the dynamic state of the physical object by using a very small perturbation. Experimental control of chaos has been successfully realized first by Ditto et al., 1990 on the parametrically driven magnetoelastic ribbon and then by many others on mechanical, electronic, biological and chemical systems (see Ott et al., 1990).

An alternative mathematical formalism for explanation of control phenomenon is provided by synchronization theory (Blekhman, 1988; Lursmanashvili et al., 1987; Pikovsky et al., 2003; Rosenblum et al., 1996, 1997). The crux of this approach is existence of some critical parameter in the system that causes its relaxation. Then small periodic impact can synchronize relaxation of the whole system with the period of impact, if some force regularly drives the system close to the critical state. Let us consider some relaxation process in which the intensity $U_t$ (it can be related to voltage, stress, etc.) builds up slowly to some critical value $U^c$, when $U_t=U^c$, the intensity drops instantly to some initial value. Then application of synchronizing pulses of relatively small amplitude $U_s$ and of very short duration may impose coherency of these drops with the timing of pulses, as now the condition of criticality is $U_t+U_s=U^c$ or, in the case of sinusoidal impact, $U_t+a\sin(\omega t+\phi)=U^c$, where $\omega$, $a$ and $\phi$ are accordingly the angular frequency, phase and amplitude of periodic impact. That means that intensity drops occur, when the increasing value of $U_t$ is equal to $U^c-a\sin(\omega t+\phi)$. It has been shown (Blekhman, 1988; Pikovsky et al., 2003) that synchronization may appear at even weak coupling between objects with significantly different characteristic frequencies that implies nonlinear interaction of objects.

What is the physical mechanism, leading to synchronization? In case of mechanical excitation synchronization is connected with mechanical triggering of microslips in the system that is close to critical state and thus reveals sensitive dependence on (small) external perturbation. The triggering occurs once per period.

In the case of EM forcing the driving mechanism of triggering is electrostriction (Eqs. (5) and (6)); synchronization occurs when the EM component of Coulomb stress is oscillating.

Under pure periodic EM excitation microslips occur twice per period. We suppose that EM synchronization is connected with polarization of surfaces of fixed and sliding samples. As the polarization forces arise at both polarities of applied periodic field, it seems reasonable that the synchronization follows each reversal of EM field. As the mechanical instabilities synchronize with both positive and negative sections of sinusoid (the response is symmetric) we can postulate that the additional elastic strain $u$, induced by forcing has a quadratic dependence on the intensity of electrical field $E=E_m \sin \omega t$:

$$u = kE^2$$

which is the well known expression of electrostriction in solids (compare with expressions (3) and (4)); here $k$ is some proportionality constant depending on the forcing frequency and physical properties of rock (Chernyak, 1978).

If the electromagnetic forcing contains besides periodic the constant component as well, that is:

$$E = E_c + E_m \sin \omega t,$$

after inserting Eqs. (8) into (7) the elastic response is:

$$u = kl(E_m)^2 \left\{1 + 2(E_c/E_m)^2 + 4(E_c/E_m)\sin \omega t - \cos 2\omega t\right\},$$

where $kl$ is proportionality constant, which depends on the forcing frequency, physical properties of rock and constant component intensity $E_c$. It is evident that the stick-slip response to forcing in the latter case depends on the value of ratio $E_c/E_m$. At $E_c/E_m \ll 1$ the $\cos 2\omega t$ term of Eq. (9) is dominant, which means that the slip events will occur with the double frequency of forcing, but at $E_c/E_m \gg 1$ the slip regime is governed by the $\sin \omega t$ term that is only one slip event occurs per period of forcing. These conclusions are confirmed by experiments (Fig. 6).

It seems that the stick-slip theory could benefit from our synchronization experiments, say, in assessment of significant constants of slip, such as characteristic slip distance and characteristic times for direct/evolution effects of the stick-slip process.

7. On the possibility of control (triggering and synchronization) of seismic events

7.1. MHD forcing of seismicity

Triggering effect of series of strong EM pulses on regional microseismicity regime was reported during experiments performed by the Institute of High
Temperatures (IHT RAS) at the Bishkek test area in 1975–1996, Central Asia (Tarasov et al., 1999; Jones, 2001). The anomalous seismic activity was observed 2–3 days after EM forcing. Using seismic data sets and catalogues of EM discharges we have investigated dynamics of temporal distribution of earthquakes around the test area before (1975–1983, Fig. 15a), during (1983–1988, Fig. 15c) and after (1983–199, Fig. 15e).

Fig. 15. Recurrence plots of waiting time sequences (a, c, e) and their shuffled surrogates (b, d, f) before (a, b), during (c, d) and long after (e, f) experiments with EM discharges at Bishkek test area (Central Asia).
EM discharges. It was found that during the period of these discharges (1983–1988) seismic dynamics become much more regular compared to the periods before and long after cessation of experiments (Chelidze and Matcharashvili, 2003). That is confirmed by recurrence plots and correlation dimension analysis of waiting times. Recurrence plots reveal nonlinear structure that appears during EM experiment period (Fig. 15c). The structure disappears in the shuffled sequence (Fig. 15d). Fractal (correlation) dimension of earthquake waiting times sequence decreases more than twice during EM experiments (Chelidze and Matcharashvili, 2003). After cessation of EM discharges, dynamics of earthquakes temporal distribution become more irregular than before experiments. These results may serve as an indication of imposing of ordering in the time domain on the regional seismic activity by series of strong EM pulses.

7.2. Synchronization by reservoir loading

As an example of possible synchronization of seismic process under small external influence we present results of our analysis of seismic activity around Enguri high dam reservoir located in the western Georgia. The height of the dam is 272 m, the average volume of water in the reservoir is $1.1 \times 10^9$ m$^3$. Preliminary flooding of the territory started at the end of December 1977; since 1987 the water level in reservoir changes seasonally, almost periodically (Fig. 16a). Thus we have defined three distinct periods of our analysis, namely, (i) before impoundment, (ii) flooding and reservoir filling and (iii) periodic change of water level. After the general increase of seismic activity during nonperiodic water level change, i.e. during initial loading and filling of the reservoir known as reservoir

![Graph](image-url)

Fig. 16. a) Record of the daily water level in the lake of Enguri dam from 1975 to 1993, b) log of normalized daily released seismic energy, c) phase differences between the phases of the cumulative values of the daily released seismic energy and the phases of the daily water level variation. Three straight lines indicate different behaviour of the dynamics. In particular, a tendency to phase synchronization is found for the last period, where the phase differences remain nearly constant. The phase synchronized state can be ascribed to ordering (quantization) of seismic activity (compare with Fig. 11).
induced seismicity (Talwani, 1997; Simpson et al., 1988) variation of the water level in the lake became periodic. For this time period the probability of large events decreased significantly. We suggest that this small periodic reservoir influence on the complex seismic process invokes synchronization of regional seismic activity as well as the decrease of probability of large earthquakes occurrence around reservoir due to quantization effect of periodic forcing, which prevents accumulation of large strain in reservoir surroundings. We calculated phase differences \( \Delta \phi \) between the phases of the cumulative values of the daily released seismic energy and the phases of the daily water level variation (Fig. 16b). Three straight lines indicate different behaviour of the dynamics in the mentioned three periods. In particular, a tendency to phase synchronization is found for the last period, where the phase differences remain nearly constant. The phase synchronized state can be ascribed to ordering (quantization) of seismic activity (compare with Fig. 9) under periodic reservoir-induced forcing.

8. Conclusions

Triggering and synchronization of instabilities in experimental spring-slider system were investigated by recording acoustic emission, accompanying the slip events.

Triggering was initiated by series of strong EM pulses applied to the mechanical system driven close to the critical state, namely to the (dry) rock sample, placed on the inclined supporting sample at the slope angle less than, but close to the critical slip angle. The electrical field was either parallel (the first mode) or normal (the second mode) to the slip surface. It has been found that in the first mode the EM impact triggers and in the second mode hampers the slip. The basic expression for a friction force under EM impact, containing electrical component of friction is similar to that of Coulomb law with the pore pressure term.

Experiments on the standard spring-slider system (fixed and sliding basalt samples), subjected to a constant pull and superimposed to it weak mechanical or EM periodic force in dry environment show that, at definite conditions, the system manifests the effect of phase synchronization of microslip events with the weak periodic excitation. The quality of synchronization depends on the intensity and frequency of the applied field; the corresponding Arnold’s tongue region is constructed.

Application of special techniques (measuring phase differences, phase diffusion coefficient, Shannon entropy, Recurrence Quantification Analysis) allows quantification of the strength of synchronization of microslips with EM impact.

We observe transition (bifurcation) in stick-slip from 1:2 or period doubling synchronization when two slip events occur per period of forcing to 1:1 synchronization (one slip event per period of forcing) at simultaneous action of direct \( V(0) \) and periodic \( V(p) \) voltages; transition occur at \( V(0) > V(p) \).

Acoustic emission energy distribution (analogue of frequency-magnitude plot) undergoes significant changes at variation of excitation intensity, namely, the slope of the plot is maximal in synchronization area, which means that synchronization limits the energy release associated with individual events (quantization effect). Switching off the synchronizing forcing provokes drastic increase of energy emitted by following slip event.

We conclude that our laboratory experiments give a sound principal basis for interpretation of field data on the control of seismic regime by relatively weak natural or artificial perturbations.

Acknowledgements

We acknowledge INTAS grant: #0748, 2002 and DAAD visit grant for T. Matcharashvili.

References


