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Preliminary results of forced stick-slip synchronization area studies: experiments and theoretical models

Tamaz Chelidze, Teimuraz Matcharashvili, Ekaterine Mepharidze,
Dimitri Tephnadze, Natalia Zhukova
M. Nodia Institute of Geophysics, 1, Alexidze str. 0160, Tbilisi, Georgia

Abstract

Synchronization phenomena are encountered in various fields, from mechanics to biological and social processes. In the paper, the results of laboratory experiments on the mechanical and electromagnetic synchronization of mechanical instability (slip) of a slider-spring system consisting of basalt blocks are presented. Slip events were recorded as acoustic emission bursts. The data allow delineating the synchronization region in the plot of forcing intensity versus forcing frequency for both mechanical and electromagnetic synchronization. Experiments are compared with theoretical models.

Introduction

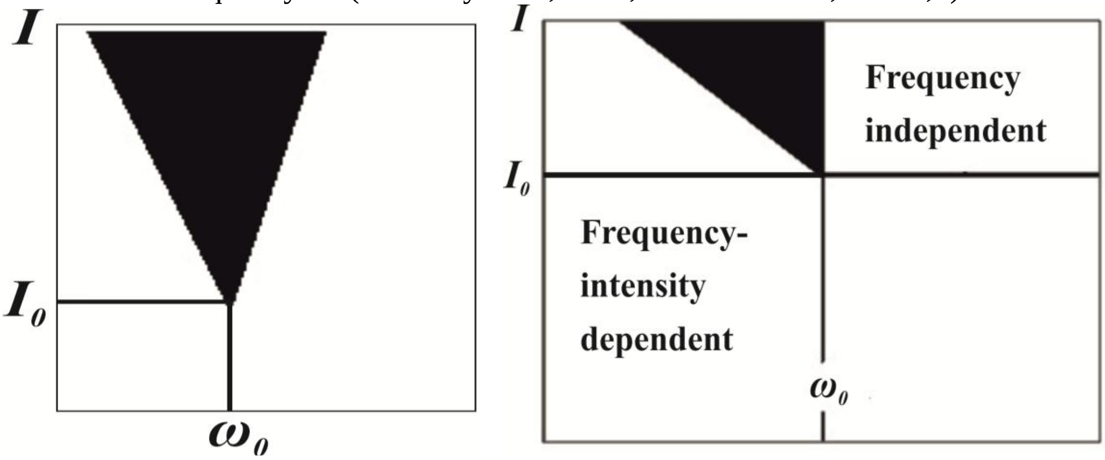
Synchronization is encountered in various fields, from mechanics to biological and economical processes (Pikovsky et al., 2003; Blekhman and Rivin, 1988). One important domain is the synchronization of seismic process and its small scale model - stick-slip by a weak external forcing (Scholz, 2003; Beeler and Lockner, 2003, Bartlow et al., 2012). As the Earth is embedded in the oscillating field of different origin with extremely wide range of frequencies, from seconds to months and years, synchronization is possible in many geophysical processes. For example there are a lot of observations that seismic activity is coupled with the action of such weak oscillating fields as Earth tides, solar activity, atmospheric pressure, electromagnetic pulses (storms), seasonal variations, and reservoir exploitation. The intensity of stress, invoked by these superimposed periodical mechanical or electromagnetic (EM) oscillations is as a rule much smaller (of the order of 0.1-1 bar) than that of the main driving force – tectonic stress (Prejean and Hill, 2009). Nevertheless, finally, this weak interaction may invoke the phenomenon of synchronization, at least, the so called phase synchronization – PS (Rosenblum et al., 1996). It is evident that these phenomena cannot be understood in the framework of traditional linear approach and that such high sensitivity to weak impact imply essentially nonlinear interactions (Kantz and Schreiber, 1997).

It should be mentioned that the papers devoted to theoretical nonlinear analysis of natural (non-forced) stick-slip equations (Becker, 2000) demonstrate beautiful phase plots with typical attractors. Similar results are obtained in theoretical studies of stick-slip under periodic forcing (Savage and Marone, 2007; Capozza et al., 2011), but the same authors also illustrate that obtaining such clear nonlinear patterns in experiments on physical models is very difficult due to a strong noise caused by the irregularity of slip surfaces of fixed and sliding blocks. In the present paper the results of laboratory experiments on the mechanical and electromagnetic (EM) synchronization of mechanical instability (slip) of a slider-spring system consisting of basalt blocks are presented and an attempt is done to find corresponding nonlinear dynamics patterns of natural and periodically forced stick-slip process, such as Arnold's tongues, Recurrence Plots etc.

Theoretical Models

The natural stick-slip can be approximated by relaxation process, where quasi-periodic sequence of slow accumulation of stress (stick phase) is followed by fast stress-drops or slips (Chelidze et al., 2010*b*) and is considered as an autonomous oscillator with a natural frequency ω_0.

The (periodically) forced stick-slip process is an example of the integrate-and fire oscillator under periodic forcing. There are many papers devoted to the problem of forced stick-slip (Beeler and Lockner, 2003, Bartlow et al., 2012; Johnson et al., 2013; Capozza et al., 2011; 2012; Savage and Marone, 2007; Guyer et al, 2013). The most general approach to a problem of forced autonomous oscillator is presented in Pikovsky et al., (2003): according to it the autonomous oscillator with natural frequency ω_0 subjected to a weak forcing of frequency ω and intensity $\boldsymbol{I}$ changes its frequency ω_0 to some different value Ω. The difference $(\omega - \omega_0)$ is called detuning: on the plot of $\boldsymbol{I}$ versus ω the area of synchronization of autonomous oscillator forms an inverse bell-shape (or triangle) area, so called Arnolds' tongue (Arnold, 1983) with a minimum at $(\omega - \omega_0) = 0$, i.e. at the point where forcing frequency is close to the natural frequency of oscillator (Fig. 1a); as the detuning increases, you need stronger forcing and at very large detuning synchronization became impossible. In many cases the phenomenon of high order synchronization can be observed at multiples of natural frequency ω_0 (Pikovsky et al., 2003; Chelidze et al., 2010*a*,*b*).



a) b)

Fig.1. Different models of synchronization area: (a) Arnold's tongue - the region on the plot of intensity $\boldsymbol{I}$ versus frequency ω of the external forcing, where synchronization of occurs in the presence of noise; ω_0 is the frequency of forcing when the minimal intensity I_0 is needed for synchronization (in absence of noise $\boldsymbol{I_0}$ equals zero); (b) nucleation or Scholz (2003) model - on the plot of $\boldsymbol{I}$ versus ω the correlation (synchronization) area is similar to Arnolds' tongue only at low forcing frequencies $\omega < \omega_0$ and at high frequencies the correlation of slips with forcing became frequency independent.

On the other hand in geophysical research the different (nucleation or Scholz) model of forced stick-slip is developed: according to it the plot of I versus ω (the correlation/synchronization area) is similar to symmetric Arnolds' tongue only at low forcing frequencies $\omega < \omega_0$ and at high frequencies the correlation of slips with forcing became frequency independent (Fig. 1b). For explanation of such asymmetry the concept of slip nucleation phase (time) is introduced (Scholz, 2003). According to this model if the period of forcing is greater than the slip nucleation time, nucleation does not hamper synchronization; but if the forcing period is less than nucleation time, the slips cannot follow forcing oscillations (detuning is too large), hence much higher intensity of forcing is needed to correlate slips with forcing. The above model was used to explain the lack of (or insignificant) correlation of earthquakes' occurrence with tidal stress variations (Beeler and Lockner, 2003; Scholz, 2003): according to them tides' period (hours) is too short compared to significant earthquake nucleation time (months, years).

Laboratory experiments on forced stick-slip (Beeler and Lockner, 2003; Bartlow et al., 2012; Savage and Marone, 2007) seem to confirm indeed that stick-slip synchronization area is strongly asymmetric like in Fig. 1b.

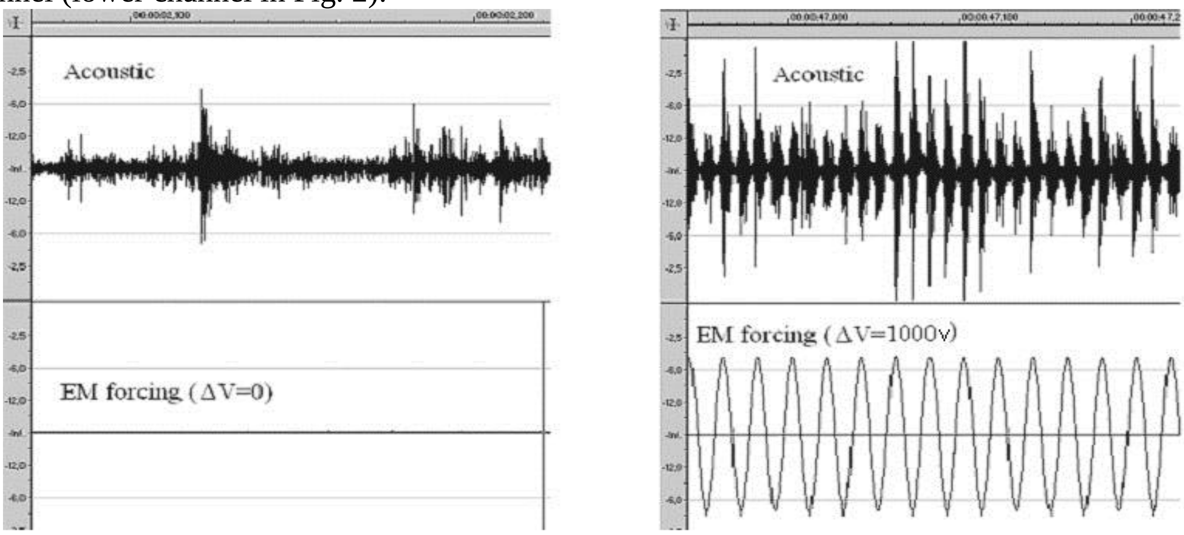
Our study is aimed to demonstrate the relevance of the presented models to laboratory experiments on the forced stick-slip.

Laboratory Experiments and Interpretation.

Experimental set up:

Experimental set up in synchronization experiments represents a system of two horizontally oriented plates of the same roughly finished basalt. The supporting and the slipping basalt blocks were saw-cut and roughly finished. The height of surface protuberances was in the range of 0.1-0.2 mm. 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 perturbations (forcing) with variable frequency (from 10 to 120 Hz) and amplitude (from 0 to 1000 V in case of EM forcing or applying from 0 to 5 V to a mechanical vibrator in case of mechanical forcing). Mechanical pull from both these forcing were much weaker (of the order of 10^{-3}-10^{-4}) compared to the pulling force of the spring.

Slip events in synchronization experiments were registered as acoustic bursts by the sound card of PC (upper channel in Fig. 2) and the EM or mechanical forcing was recorded on the second channel (lower channel in Fig. 2).



a) b)

Fig. 2. Synchronization of stick-slip by EM forcing. The upper trace is records of AE signals generated by slips; the lower channel records EM forcing; a) non synchronized (zero forcing, $\Delta V = 0$) and b) synchronized stick-slip process (forcing = 1000 V). The vertical axis shows the intensity of signal in dB and horizontal axis shows the time in msec.

Details of the setup and technique are given in (Chelidze et al., 2002; Chelidze and Lursmanashvili, 2003). In order to pick the phases of Acoustic Emission (AE) signals' relative to forcing phase onsets more precisely, a special package was developed for reducing the level of ambient noise (Zhukova et al., 2013): the result is shown in Fig.3.

Due to this methodology the weak AE signals created by microslips or precursor AE (Johnson et al., 2013) were filtered from the processing and only strong events generated by large Charaslips were selected (Fig.3).

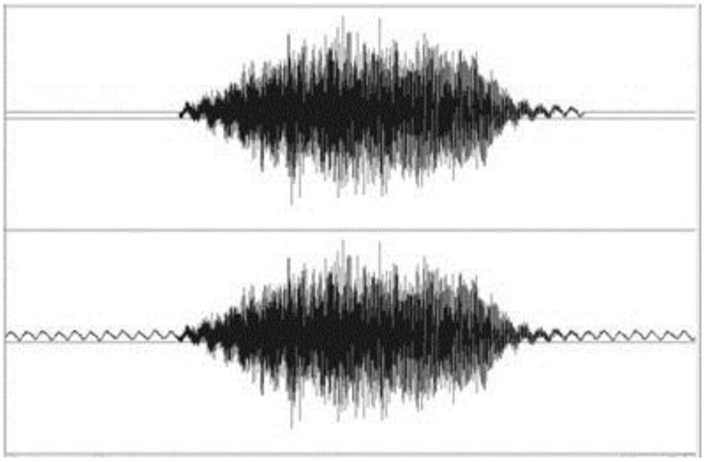


Fig. 3. Filtered (top) and original unfiltered (bottom) records of AE signal during stick-slip.

Synchronization of oscillating autonomous system of natural frequency ω_0 by forcing frequency ω results in modification of systems' natural frequency ω_0 to the so called observed frequency Ω. In our experiments the following parameters were varied: i) the frequency, ω of superimposed periodical perturbation; ii) the amplitude of the external excitation or forcing (in case of electromagnetic forcing V_a is the voltage applied to electrodes glued to contacting surfaces of fixed and pulled blocks; in case of mechanical forcing V is the voltage applied to mechanical vibrator).

Measuring synchronization strength:

Last decades several new approaches were suggested to quantify the complexity/synchronization of processes by analysis of measured time series (Blekhman, 1988; Pikovsky et al., 2003; Chelidze and Matcharashvili, 2015). The possible measures for quantification of synchronization are: generalized phase difference; mutual information; conditional probability of phases; flatness of stripes of synchrograms or stroboscopic technique; coefficients of phase diffusion (Chelidze and Matcharashvili, 2013, 2015). The other methods stem from the information theory including Shannon or Tsallis entropy, algorithmic complexity etc. It should be stressed that both laboratory stick-slip and EQ source evolution can be considered as the integrate and fire type processes, where the acoustic/seismic signals contain well-defined marked events corresponding to slips/acoustic bursts. To deal with relatively short time series new tests have been proposed such as recurrence plots (RP) and recurrence quantitative analysis (RQA). In the case of very restricted statistics (tens of events) less demanding methods, such as Shuster test (Schuster, 1897) can be used.

Synchronization at electromagnetic forcing - Arnold's tongue:

The example of synchronized and non-synchronized stick-slip at electromagnetic (EM) forcing are shown in Fig. 2. The electric field in this case was normal to the sliding plane. Synchronization was observed only at some definite sets of parameters (spring stiffness K_s, forcing frequency f, forcing intensity ΔV_a). Several methods were used for measuring synchronization strength depending on forcing parameters, which are presented in Chelidze and Matcharashvili (2013, 2015), Chelidze et al., (2002, 2003, 2005, 2010*a*,*b*).

Here we focus on the "phase diagram" for variables f and ΔV_a or so-called Arnold's tongue (see Pikovsky et al., 2003), which is presented in the Fig. 4.

The minimum forcing intensity $\Delta V_a \approx 400\,\mathrm{V}$ needed for a strong synchronization corresponds to the forcing frequencies in the range 60-80 Hz.

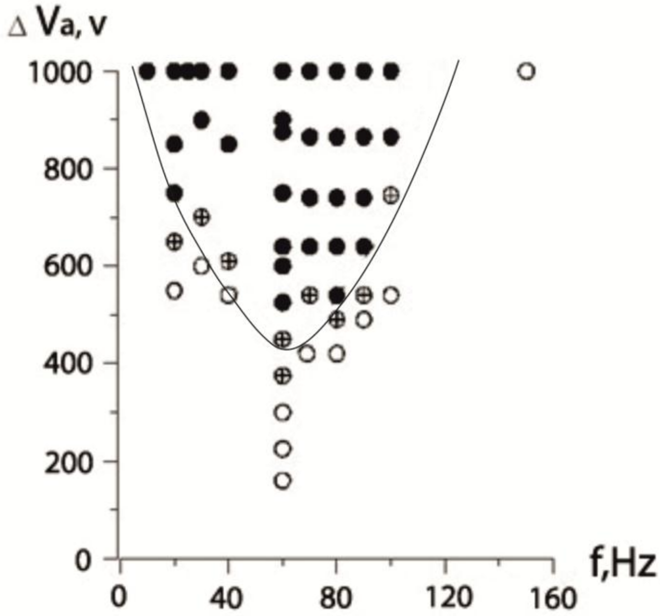


Fig. 4. Stick-slip synchronization area (Arnold's tongue) for various intensities (V_a) and frequencies (f) of the external periodic EM forcing. Filled circles – strong, circles with crosses – intermittent and empty circles – absence of synchronization (Chelidze et al., 2003, 2005, 2010a,b).

In our experiments with EM forcing besides (1:1) locking the high order synchronization (1:n) was also observed, where $n > 1$ is the number of synchronized slips generated by one forcing period (Chelidze et al., 2002, 2003, 2005, 2010 a, b, 2015).

Synchronization by mechanical forcing:

Weak mechanical periodic perturbations also imposes ordering on the slip, namely a phase synchronization. Mechanical forcing was realized by the vibrators of geophone "CB-5" or "CB-20". The intensity of mechanical vibration was regulated by the voltage V applied to the vibrator. In our experiments with mechanical forcing as a rule the high order phase synchronization (HOS) was observed, namely, the triggered slip occurred only after several tens of forcing periods. High-order synchronization means that the forcing (ω) and observed (Ω) frequencies in the system are related to each other by some winding ratio ($n \div m$) that is $n\omega = m\Omega$ (Chelidze et al., 2010*a,b*). The winding ratio $n \div m$ at mechanical forcing was in the range 80:1 to 200:1, depending on the experimental conditions.

The stick-slip experiments with mechanical forcing were carried out at following parameters: the stiffness of the spring, $K_s = 235.2$ N/m; the voltage applied to vibrator was 0.25V, 0.5 V, 0.75V, 1 V, 1.5 V, 2 V, 2.5V 3 V; the frequency of forcing was varied in the range 5-120 Hz and the natural frequency of the sensor was 20 Hz.

In order to assess the strength of phase synchronization phase differences between the phases of periodic forcing signal and the onsets of AE burst were picked out (in Figs. 5 a-h on X axes are shown phase differences value and on Y axes – the number of events in a bin; bin is taken equal to 1/15th of the forcing period) and the corresponding histograms were compiled; the binned distribution was approximated by parabola.

As a model for the phase distributions of events a polynomial of the second degree (parabola) was used:

$$f(x) = p_1 x^2 + p_2 x + p_3$$

The parabolic plot is considered as a proxy of probability density function (PDF) of a number of AE signals in the certain range of forcing phases y_i : the width of parabola is a proxy of

PDF width. The optimal parameters $p_1, p_2, p_3....$ of the polynomial were calculated using the least squares method for minimization of the residual between parabola and experimental values R^2:

$$R^2 = \sum_{i=1}^{n} \left[y_i - (p_1 x_i^2 + p_2 x_i + p_3) \right]^2$$

Where y_i is the number of events in the i^{th} bin, i - is a bin's current number.

The width of the parabola depends on the parameter p_1. The half-width of the parabola (a proxy of half-width of PDF) is equal to $\frac{1}{2} p_1$.

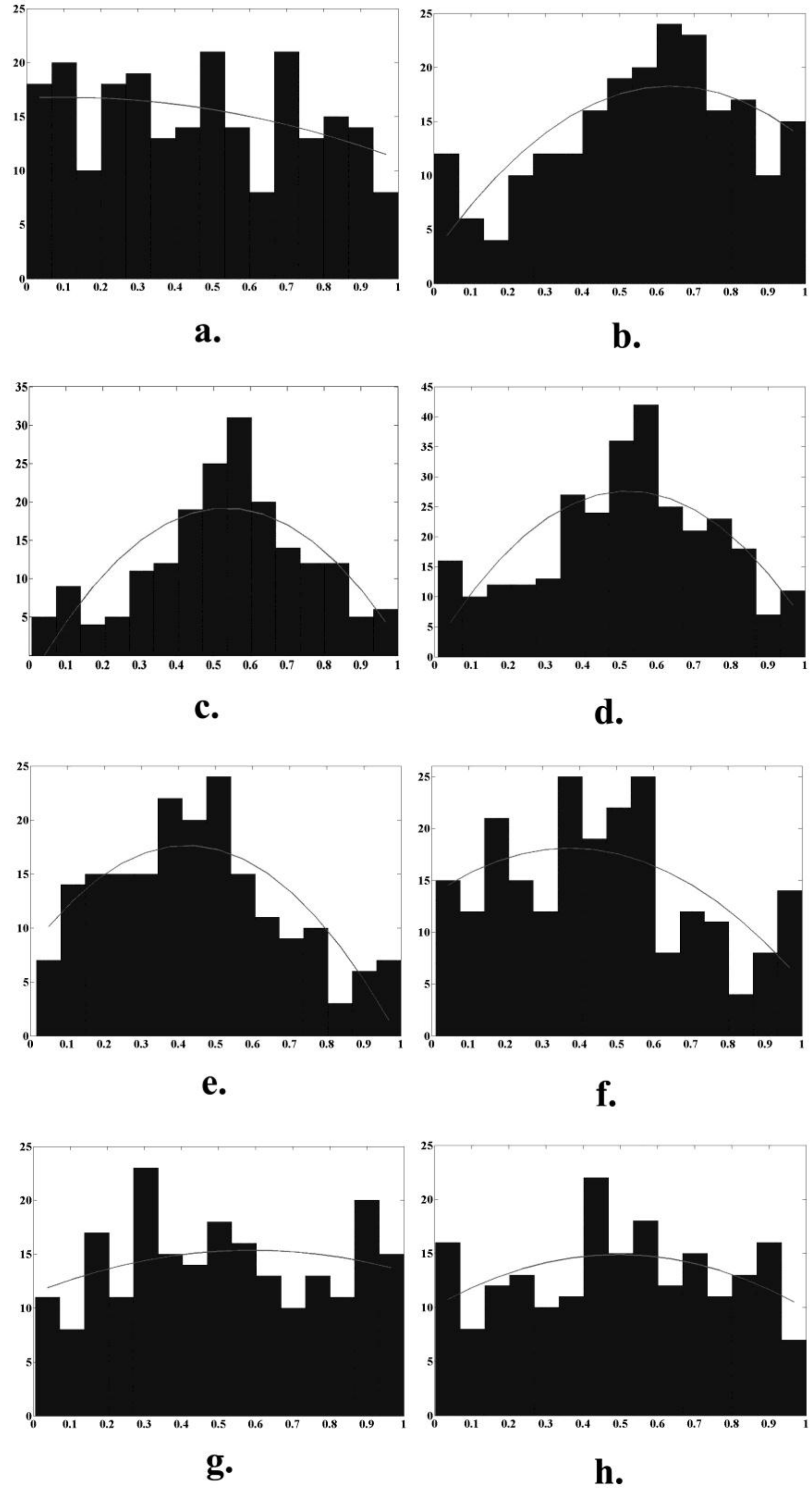


Fig. 5. PDF of number of AE signals in the certain range of forcing phases (in 1/15th bins of the forcing period) for the stiffness of the spring $K_s = 235.2$ N/m and forcing 1V (natural frequency of sensor 20 Hz). Forcing frequencies: (a) 5Hz; (b) 10Hz; (c) 20Hz; (d) 30Hz; (e) 40Hz; (f) 50Hz; (g) 80 Hz; (h) 120 Hz.

In order to assess the strength of phase synchronization and compile the Arnolds' plot phase differences between the phase of periodic forcing signal and the onset of AE burst was picked out and the plots of probability density functions (PDF) of number of AE signals at certain phases of forcing (in bins of period) were constructed (Fig. 5 a-h).

Arnold's tongue at mechanical forcing:

For randomly distributed AE signals PDF plots are almost flat and for increased strength of synchronization are bell curve like with the half-width depending on the synchronization strength.

The data obtained allow construction of phase space plot of synchronization strength dependence on intensity and frequency of forcing or Arnold's plot (Fig.6). Hollow rings mean absence, rings with crosses – moderate and filled rings – good synchronization.

The minimum forcing intensity needed for a strong mechanical synchronization corresponds to the forcing frequencies 20-40 Hz, which is not very far from the optimal forcing frequencies at EM synchronization – 60 Hz (Fig. 4). The filled dots correspond to good synchronization, hollow dots – to absence and dots with crosses – to moderate synchronization.

We guess that the similarity in optimal forcing frequencies can be related to the identity of configuration of sliding and fixed blocks of basalt as well as to closeness of other stick-slip parameters (spring stiffness, drag velocity etc) in both EM and mechanical synchronization experiments.

Obtained results confirm the inverse bell-shape configuration of the mechanically forced stick-slip synchronization area similar to EM forcing data. The minimal forcing frequency/intensity required for synchronization should provide optimal friction conditions or friction stabilization (Cochard et al., 2001; Capozza et al., 2012). Here we'd like to comment that friction stabilization by weak periodic forcing does not mean complete elimination of stick-slip: experimental data (Fig.3 in Cochard et al, 2001,) show that even at minimal friction in forced experiments there are still small scale synchronized stick-slip events; so instead of the term friction stabilization it seems better to use the term stick-slip minimization or stick-slip quantification.

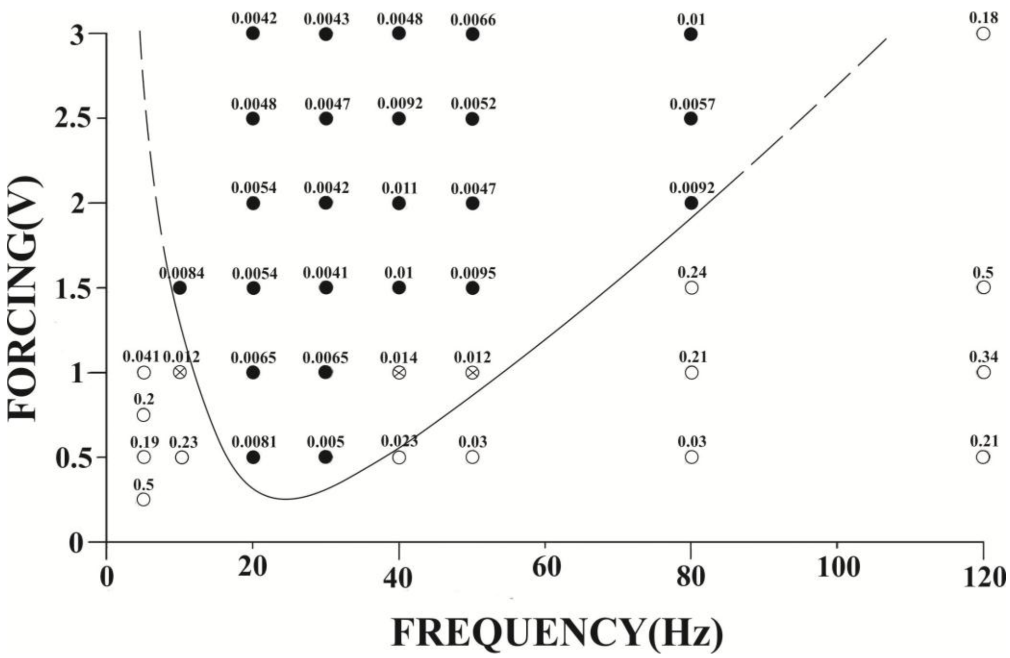


Fig.6. Phase space plot of synchronization strength (Arnold's tongue) expressed as half-widths $\frac{1}{2}p_1$ of parabola plots (proxies of PDFs) in Fig.5 a-h for the spring stiffness $K_s = 235.2$ N/m. Hollow dots mean absence (half-width $\frac{1}{2}p_1 > 0.014$), dots with crosses – moderate $0.012 \le \frac{1}{2}p_1 \le 0.014$ and filled dots – good synchronization. $\frac{1}{2}p_1 < 0.012$.

In addition to Arnold’s plot some other nonlinear tests were performed, namely Recurrence Plots (RP) were composed and corresponding Recurrence Quantitative Analysis (RQA) was performed (Marwan et al, 2007; Webber, Marwan, 2015) using Visual Recurrence Analysis (VRA) tools (Kononov, 2006). RP plots for original data contain horizontal and vertical lines/clusters, which mean that during both natural and driven stick-slip some states are “laminar”, i.e. they change slowly or do not change at all. We can attribute laminar states of AE waiting times to the periods, when the upper plate is stuck till strain from the spring became equal to friction force.

Recurrence Plots for various frequencies and constant forcing intensity 1.5 V show clear recurrence structures at frequencies 20-40 Hz, which are fading at higher frequencies (the plots became similar to RP of random sequence) in accordance with the Arnold's plot (Fig. 6).

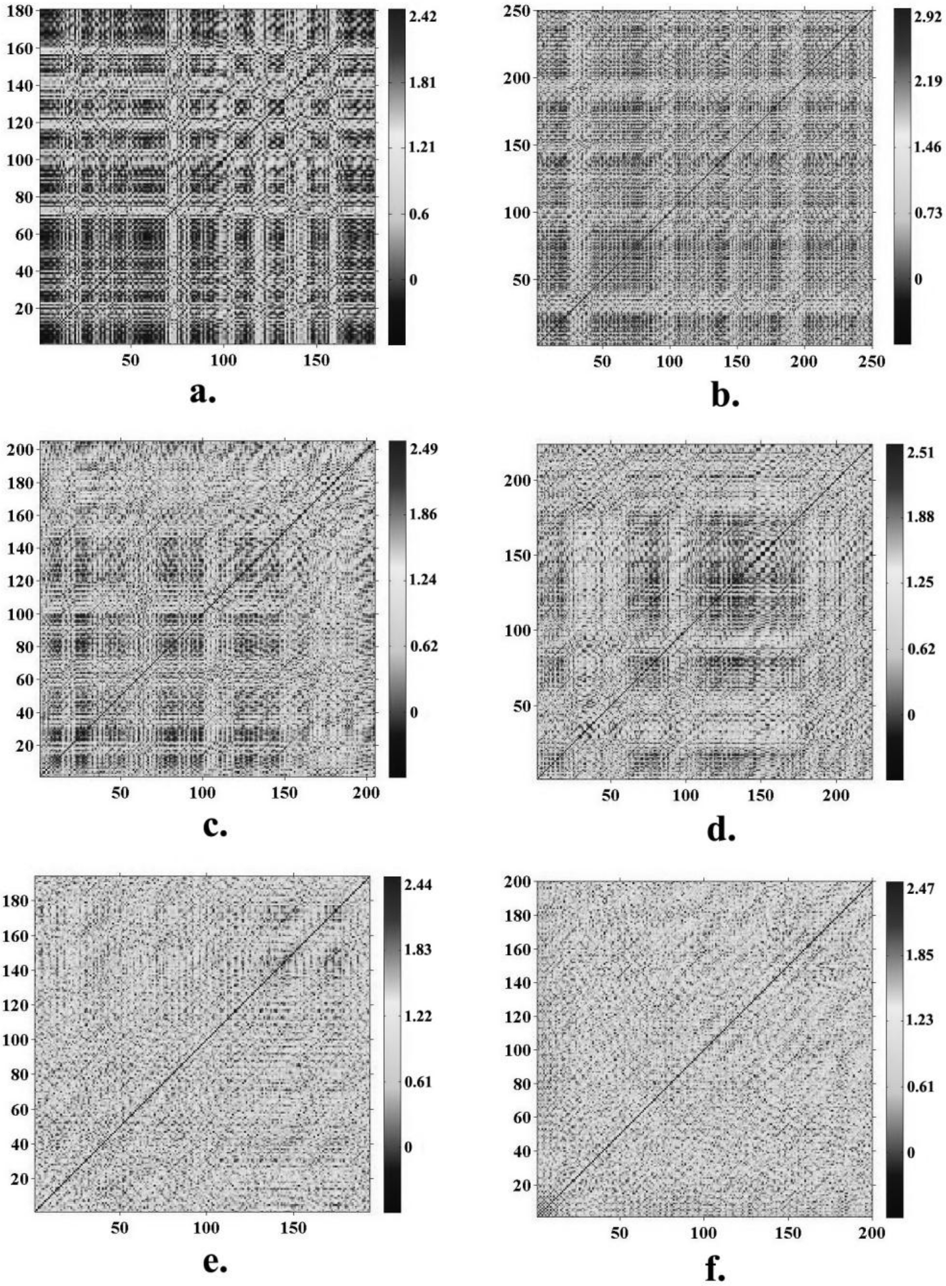


Fig. 7. Recurrence plots of slip-generated AE signals (original sequence of events) for the stiffness of the spring K_s =235.2 N/m and forcing 1.5V (natural frequency of sensor 20 Hz).

Synchronization at forcing frequencies: 20Hz (a); 30Hz (b); 40Hz (c); 50Hz (d); 80Hz (e); 120Hz (f).

Calculation of quantitative parameter (namely the percent of determinism %DET) of recurrences at various frequencies and intensities of forcing by RQA approach (Marwan et al, 2007), presented in Fig. 8, show that the %DET significantly increases in the frequency range from 20 to 60 Hz and at intensities of forcing larger than 0.5V, again in accordance with Arnold's plot (Fig.6).

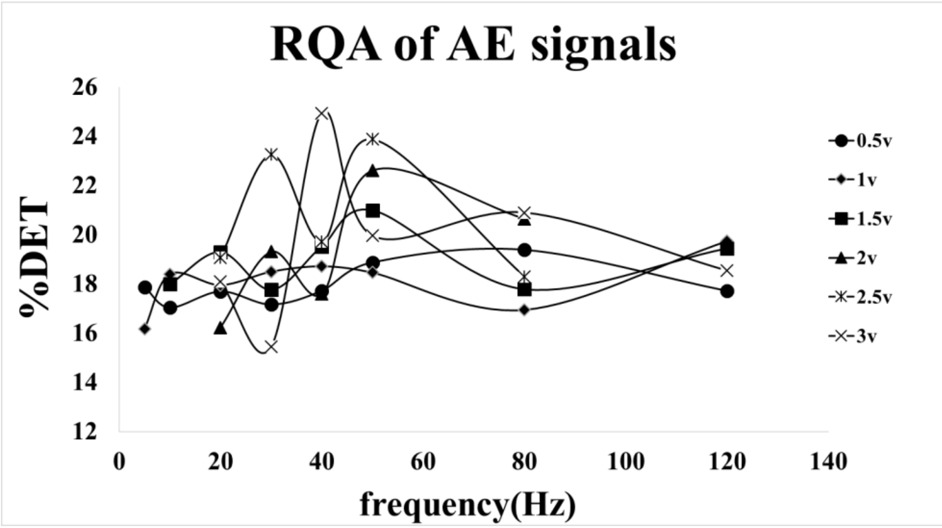
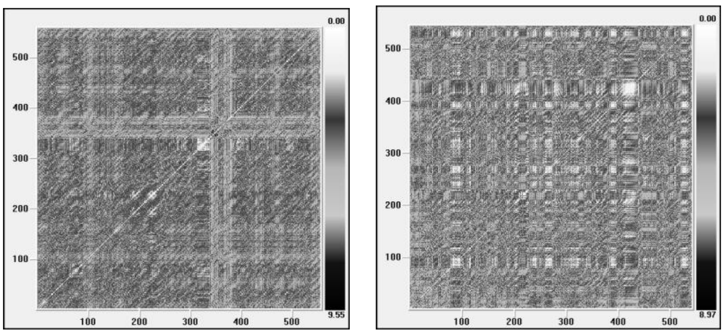


Fig.8. %DET versus the frequency of forcing at various intensities of forcing (original sequence of events).

The previous results (Figs.6-9) are related to the original sequences of AE events. It was interesting to consider also the smoothed sequences as according to general statistics terminology they correspond to a conditional rate (conditional intensity) models in the point process theory. We used the rates, obtained by Savitsky-Golay (S-G) filtering. Savitzky-Golay filter helps to resolve smoothing problem in the time domain as the magnitude of the variations in the data, i.e., the value of the local extremes, is preserved to a large extent (Press et al., 1997). The operation of smoothing performs actually a low-pass filtering of the sequence, which in turn allow revealing long-range correlations in the data. RQA calculations for the waiting times (WT) data, smoothed by Savitzky-Golay filter (Fig.9) indicate that the sequences of WT of the natural stick-slip (left plot) is less ordered than that of the periodically forced one (right plot); increase in the determinism %DET from 67% for natural process to 84% in the forced stick-slip.



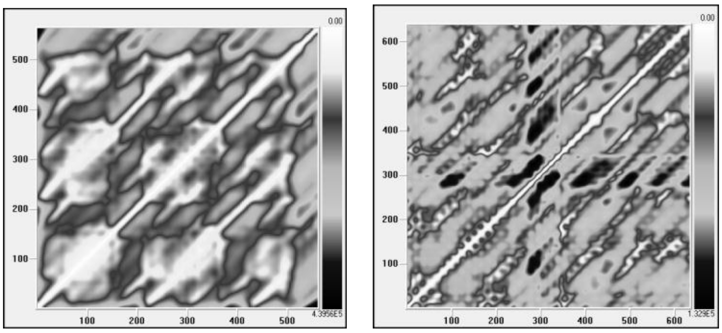


Fig.9. Visual Recurrence Analysis (VRA) plots (Kononov, 2006) of waiting times sequences of acoustic emissions (AE) smoothed by Savitzky-Golay filter: left column - RP (top) and VRA (bottom) plots for waiting times sequences of AE generated during natural stick-slip, right column - RP (up) and VRA plots of waiting times sequences of AE generated during stick-slip under periodic mechanical forcing (spring stiffness of 235 N, drag velocity 0.7 mm/s, forcing frequency 20 Hz

According to our experiments, the intensity-frequency phase space plot for forced stick-slip (Fig.7) follows inverse bell-shape pattern of Arnold model (Fig.1a), though a bit skewed at higher frequencies. We guess that the absence of the high-frequency branch declared in some studies of forced stick-slip (Beeler and Lockner, 2003; Bartlow et al., 2012; Savage and Marone, 2007) and explained in terms of Scholz model (Fig.1b) in principle can be due to some experimental restrictions (e.g. to a high inertia of the loading frame, transition from the synchronization regime to modulation mode etc). Besides, it should be noted that in some experiments of the cited authors the incipient high-frequency branch of Arnold plot seems to be present (see Figs. 5a, 7a in Beeler and Lockner, 2003 and Fig. 3a in Bartlow et al., 2012).

At the same time we cannot exclude the possibility of the strongly asymmetric pattern shown in Fig.1b: for example, simulations of frictional slip triggered by mechanical vibrations (Capozza et al., 2012) show that in some specific conditions, namely in case of very strong attractive interparticle forces the time-averaged friction coefficient $< \mu >$ at high enough forcing frequencies became frequency independent. At the same time the values of $< \mu >$ in this high frequency domain are very low, which seems to be in contradiction with nucleation model (according to it friction is very high during nucleation period).

We presume that the frictional behavior can be very different depending on many variables: rate, state, normal and pore pressure, gorge characteristics, intensity and frequency of forcing etc. This makes the response of the sliding systems to external forcing extremely variable. Mapping of Arnold tongue plot is informative for solving friction optimization/stabilization problem by application of weak external forcing. Application of nonlinear dynamics methods such as Recurrence Plots and Recurrence Quantification Analysis can be very helpful in analysis of forced stick-slip process.

Conclusions

In the paper the results of laboratory experiments on the mechanical or electromagnetic periodic forcing of mechanical instability (slip) in a slider-spring system are presented. Slip events were recorded as acoustic emission bursts. The data allow delineating approximately the synchronization regions (Arnold's tongues) in the plot of forcing intensity versus forcing frequency for both mechanical and electromagnetic synchronization.

The minimum forcing intensity needed for a strong mechanical synchronization is not very far from the optimal forcing frequencies at EM synchronization. We guess that the similarity in optimal forcing frequencies can be related to the identity of configuration of sliding and fixed blocks of basalt as well as to closeness of other stick-slip parameters (spring stiffness, drag velocity, normal stress/sliding block weight etc) in both EM and mechanical synchronization experiments.

Our experiments with both electromagnetic and mechanical periodic forcing support the general model of stick-slip synchronization area (known as Arnold’s tongue), whose geometry is close to symmetric inverse bell-curve form; in this model both low- and high-frequency branches of forcing intensity vs frequency plot are frequency dependent. At the same time frictional motion depends on many variables like rate, state, normal and pore pressure, gorge characteristics, intensity and frequency of forcing etc other configurations of synchronization area cannot be excluded.

The results obtained by analysis of half-width of phase difference distribution are confirmed by other method, namely calculation of Recurrence Plots and Recurrence Quantification Analysis. The results can be important in tribology as the minimum of Arnold's tongue corresponds to optimal friction control (friction stabilization) by application of minimal external mechanical/EM forcing. Further investigations in this direction are needed to describe in detail the complexity of frictional motion.

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References

Arnold, V., 1983. Notes on the perturbation theory for the problems of Matieu type, Russ. Mat. Surveys, 38, pp. 215-233.

Beeler, N. M., Lockner, D. A. 2003.Why earthquakes correlate weakly with the solid Earth tides: Effects of periodic stress on the rate and probability of earthquake occurrence. J. Geophys. Res., 108, B2391, doi:10.1029/2001JB001518,

Bartlow, N. M., Lockner, D. A., and Beeler N. M., 2012. Laboratory triggering of stick-slip events by oscillatory loading in the presence of pore fluid with implications for physics of tectonic tremor, J. Geophys. Res., 117, B11411, doi:10.1029/2012JB009452.

Becker, T., 2000. Deterministic chaos in two state-variable friction sliders and the effect 0f elastic interactions. In: “GeoComplexity and Physics of Earthquakes” (Eds. J. Rundle, D. Turcotte, W. Klein), pp. 5-27.

Blekhman, I.I. and Rivin E.I. 1988. Synchronization in Science and Technology. Asme Press Translations.

Capozza, R., Rubinstein, Sh., Barel, I., Urbakh, M.,and Fineberg, J., 2011. Stabilizing Stick-Slip Friction. Phys. Rev. Letters, v.107, 024301; DOI: 10.1103/PhysRevLett.107.024301.

Capozza R., Vezzani A., Vanossi A., Zapperi S., 2012. Triggering Frictional Slip by Mechanical Vibrations, Tribol. Lett. 48, pp. 95–102; DOI 10.1007/s11249-012-0002-0.

Chelidze, T., Varamashvili, N., Devidze, M., Tchelidze, Z., Chikhladze, V., Matcharashvili, T., 2002. Laboratory Study of Electromagnetic Initiation of Slip, Annals of Geophysics, 45, pp. 587-599.

Chelidze, T., Lursmanashvili, O., 2003. Electromagnetic and mechanical control of slip: laboratory experiments with slider system, Nonlinear Processes in Geophysics, 20, pp. 1-8.

Chelidze T., Matcharashvili, T., Gogiashvili, J., Lursmanashvili, O, Devidze, M., 2005. Phase synchronization of slip in laboratory slider system, Nonlinear Processes in Geophysics, 12, 1-8.

Chelidze, T., Lursmanashvili, O., Matcharashvili, T., Varamashvili, N., Zhukova, N., Mepharidze, E., 2010, High order synchronization of stick-slip process: experiments on spring-slider system, Nonlinear Dynamics, DOI 10.1007/s11071-009-9536-6. ***a***.

Chelidze, T., Matcharashvili, T., Lursmanashvili, O., Varamashvili, N., and Zhukova, N., Meparidze, E., 2010. Triggering and Synchronization of Stick-Slip: Experiments on Spring-Slider System. In: Geoplanet: Earth and Planetary Sciences, Volume 1, 2010, DOI:

10.1007/978-3-642-12300-9; Synchronization and Triggering: from Fracture to Earthquake Processes. Eds.V.de Rubeis, Z. Czechowski and R. Teisseyre, pp.123-164. ***b***.

Chelidze, T., and Matcharashvili, T., 2013. Triggering and Synchronization of Seismicity: Laboratory and Field Data - a Review. In: Earthquakes – Triggers, Environmental Impact and Potential Hazards. (Ed. K. Konstantinou), Nova Science Pub.

Chelidze, T., and Matcharashvili, T., 2015. Dynamical Patterns in Seismology. In: Recurrence Quantification Analysis: Theory and best practices. (Eds. C.Webber and N.Marwan). Springer Cham Heidelberg, pp. 291-335.

Cochard, A., Bureau, L., and Baumberger, T. 2001. Stabilization of frictional sliding by normal load modulation: A bifurcation analysis. Trans. ASME, J.Appl.Mech, 70, 220

Guyer, R. A., Le Bas, P-Y., Trugman, D., and Marone, C., 2013. Acoustic emission and microslip precursors to stick-slip failure in sheared granular material. Geophys. Res. Lett., 40, pp. 1–5, doi:10.1002/2013GL057848.

Johnson, P. A., Kaproth, B. M., Scuderi, M., Ferdowsi, B., Griffa, M., Carmeliet, J., Guyer, R. A., Le Bas, P-Y., Trugman, D., Marone, C., 2013. Acoustic emission and microslip precursors to stick-slip failure in sheared granular material, Geophysical Research Letters, 40, 21, pp. 5627–5631.

Kantz, H., Schreiber T., 1997. Nonlinear time series analysis, Cambridge University Press, Cambridge.

Kononov, E. 2006. Visual Recurrence Analysis. www2.netcom.com/~eugenek/page6.html.

Marwan N, Romano MC, Thiel M, Kurths J: 2007. Recurrence plots for the analysis of complex systems. Phys Rep, 438:237–329.

Pikovsky, A., Rosenblum, M. G., Kurths. J., 2003. Synchronization: Universal Concept in Nonlinear Science, Cambridge University Press, Cambridge.

Prejean, S., Hill, D., 2009. Dynamic triggering of Earthquakes. In: Encyclopedia of Complexity and Systems Science, R. A. Meyers (Ed.), Springer, pp. 2600-2621.

Press, W., Teukolsky, S. A., Vetterling, W.T., Flannery, B. P. 2007. Numerical Recipes: The Art of Scientific Computing (3rd ed.). New York: Cambridge University Press.

Rosenblum, M. G., Pikovsky, A., Kurths, J., 1996. Phase synchronization of chaotic oscillators. Phys. Rev. Lett., 76, pp. 1804-1808.

Savage, H., Marone, C., 2007. Effects of shear velocity oscillations on stick-slip behavior in laboratory experiments, J. Geophys. Res.: Solid Earth, 112B, DOI: 10.1029/2005JB004238.

Scholz, C. H., 2003. Good Tidings, Nature, 425, pp. 670-671.

Schuster, A., 1897. On lunar and solar periodicities of earthquakes. Proc. R. Soc. Lond. 61, 455–465

Webber, Ch., Marwan, N.(Eds). 2015.Recurrence Quantification Analysis, Theory and Best Practices. Springer Cham Heidelberg.

Zhukova, N., Chelidze, T., Matcharashvili, T., 2013. Automatic onset time picking of acoustic signals. Journal of Georgian Geophysical Society, Issue (A), Physics of Solid Earth, v.16a, 2013, pp.115-119.

ფორსინგის პირობებში არამდგრადი ხახუნის (სტიკ-სლიპის) სინქრონიზაციის არის შესწავლის წინასწარი შედეგები : ექსპერიმენტები და თეორიული მოდელები

თამაზ ჭელიძე, თეიმურაზ მაჭარაშვილი, ეკატერინე მეფარიძე, დიმიტრი ტეფნაძე, ნატალია ჟუკოვა

რეზიუმე

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Предварительные результаты синхронизации неоднородного трения (Стик-Слип) при внешнем воздействии: теоритическая модель эксперимента

Тамаз Челидзе, Теймураз Мачарашвили, Екатерина Мепаридзе, Дмитрий Тепнадзе, Наталья Жукова

Резюме

Явление синхронизации наблюдается во многих направлениях, как в механическом, биологическом, так и в социальном. В статье приведены результаты синхронизации лабораторных экспериментов системы скольжения пружины при механическом и электрическом воздействии. Скольжение фиксировалось в виде импульсов акустической эмиссии. Такие данные дают возможность ограничить область синхронизации (воздействие) в условиях приложенного воздействия частот и интенсивности. Также было произведено сравнение экспериментальных данных с теоритическими моделями.