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Arnold's tongues at electromagnetic and mechanical synchronization of stick-slip

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Abstract

Synchronization phenomena are encountered in various fields, from mechanics to biological and social processes. Thus it is only natural that synchronization is observed in many geophysical fields, as the Earth is embedded in the oscillating field of different origin with extremely wide range of frequencies, from seconds to months and years. These large-scale natural processes can be modeled in laboratory. In the paper, the results of laboratory experiments on the mechanical and electromagnetic synchronization of mechanical instability (slip) of a slider-spring system are presented. Slip events were recorded as acoustic emission bursts. The data allow delineating approximately of the synchronization regions (Arnold's tongues) in the plot of forcing intensity versus forcing frequency for both mechanical and electromagnetic synchronization.

Introduction

Synchronization is encountered in various fields, from mechanics to biological and economical processes (Pikovsky et al., 2003). Thus it is only natural that synchronization phenomena are observed in many geophysical fields, as the Earth is embedded in the oscillating field of different origin with extremely wide range of frequencies, from seconds to months and years. For example there are a lot of (disputable) 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; 1997). 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).

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 mechanical vibrator in case of mechanical forcing). Mechanical pull from both these forcing were much weaker compared to the pulling force of the spring; the electric field was normal to the sliding plane.

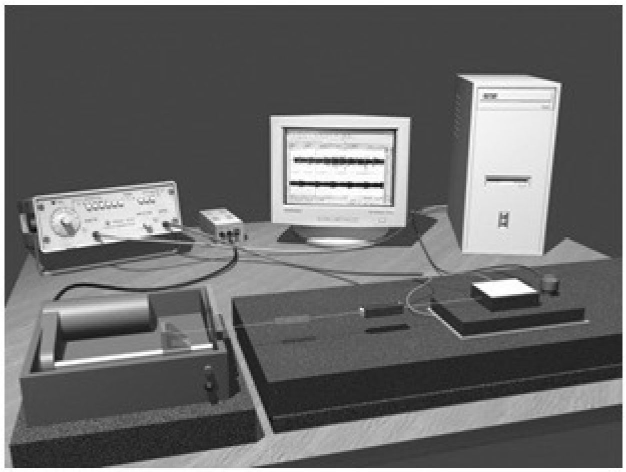


Fig.1. The scheme of laboratory installation for studying stick-slip synchronization.

Slip events in synchronization experiments were registered as acoustic bursts by the sound card of PC. The scheme of installation is presented in Fig. 1. Details of the setup and technique are given in (Chelidze et al., 2002; Chelidze and Lursmanashvili, 2003; Chelidze and Varamashvili, 2010). In order to pick phases of 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.2.

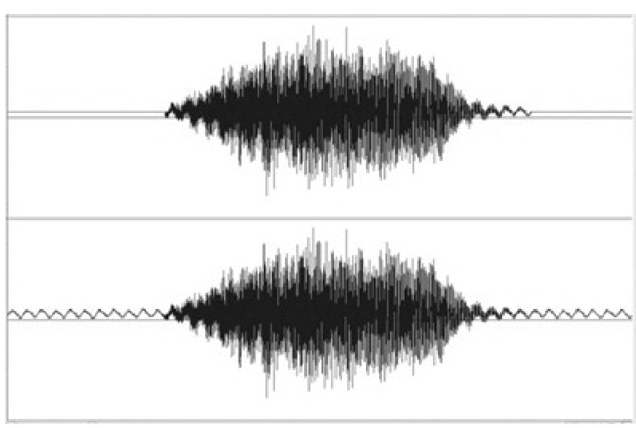
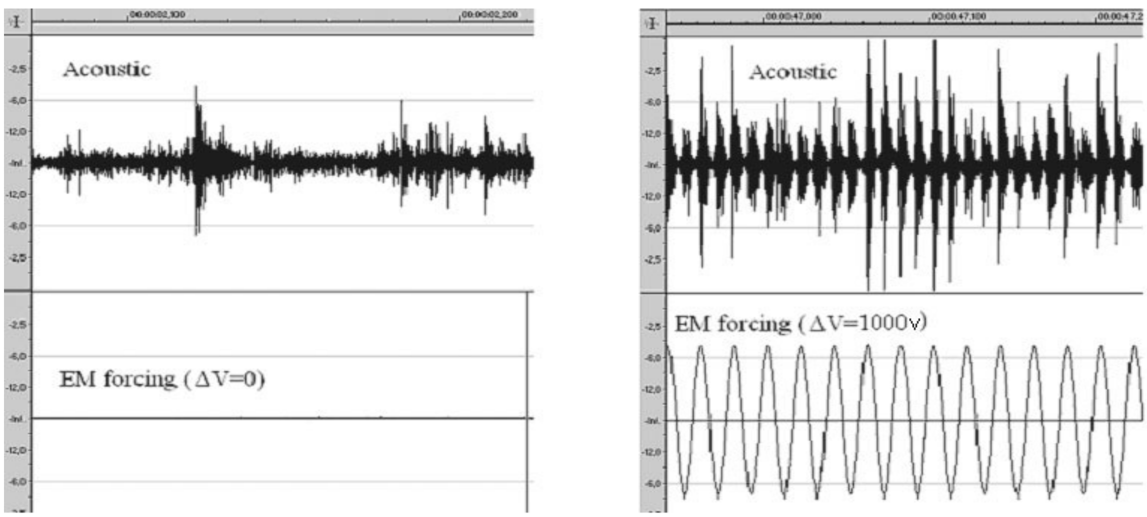


Fig. 2. Filtered (up) and original unfiltered (down) records of AE signal during stick-slip.

Synchronization parameters.

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 stiffness of the spring, K_s; ii) the frequency, f of superimposed periodical perturbation; iii) the amplitude of the external excitation or forcing (here voltage V_a is applied to electrodes in case of electromagnetic forcing or voltage V applied to mechanical vibrator in case of mechanical forcing); iv) the velocity of drag, v_d; v) the normal (nominal) stress σ_n.



a) b)

Fig. 3. The upper traces record AE signals generated by slips; the lower channel records EM forcing; a) – non synchronized and b) - synchronized (expanded) stick-slip process. The vertical axis shows the intensity of signal in dB and horizontal axis shows the time.

Synchronization at electromagnetic forcing - Arnold's tongue.

The example of synchronized and non-synchronized stick-slip at electromagnetic (EM) forcing are shown in Fig. 3.

Synchronization was observed only at some definite sets of parameters (K_s, f, V_a). The "phase diagram" for variables f, and V_a or so-called Arnold's tongue (see Pikovsky et al., 2003) is presented in the Fig. 4.

The minimum forcing intensity needed for a strong synchronization corresponds to the forcing frequencies 60-80 Hz.

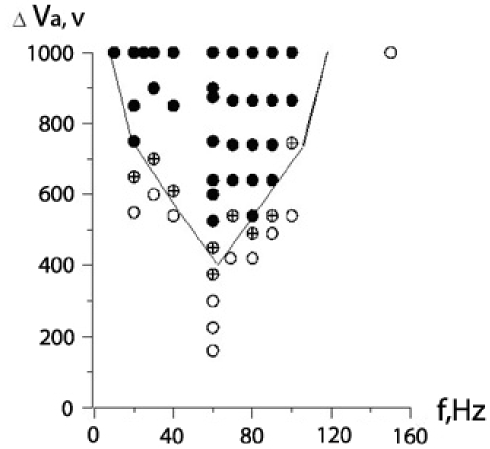


Fig. 4. Stick-slip synchronization area (Arnold's tongue) for various intensities (V_a) and frequencies (f) of the external periodic EM forcing. Filled circles – strong, circles with crosses – intermittent and empty circles – absence of synchronization.

Synchronization affects not only waiting times, but also frequency-energy distribution. Decrease of contribution of extreme events at synchronization is confirmed by calculation of the coefficient of variation CV (CV=standard deviation/mean). As it is shown in Fig.5, 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 AE events (quantization effect).

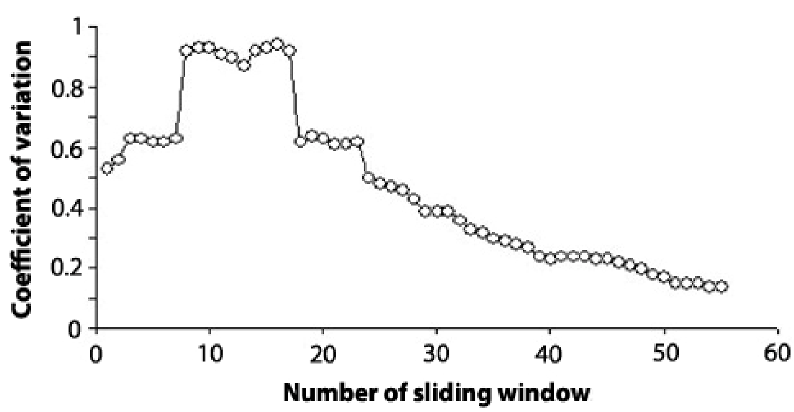


Fig. 5. Coefficient of variation of power of acoustic emission time series at increased external forcing for 500 data length sliding window with 50 data shift. The first 20 windows correspond to no or very weak forcing; windows from 50 to 56 correspond to maximal forcing.

Synchronization by mechanical forcing.

Relatively weak mechanical periodic perturbations also imposes some ordering on the slip, namely a phase synchronization. Mechanical forcing was realized by the vibrator "CB-5" for normal directed forcing and by "CB-20" for tangential directed forcing. The intensity of mechanical vibration was regulated by the voltage applied to the vibrator.

In our experiments with mechanical forcing as a rule the high order phase synchronization was observed, namely, the triggered slip occurred only after several tens of forcing periods. High-order synchronization (HOS) 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., 2010a, 2010b). The winding ratio $n \div m$ at mechanical forcing was in the range 80:1 to 200:1, depending on the experimental conditions.

The experiments with mechanical forcing were carried out at following parameters: the stiffness of the spring, K_s =78.4 N/m, 235.2 N/m and 1705.2 N/m; the voltage at vibrator was 0.5 V, 1 V, 1.5 V, 2 V. 3 V; the frequency of forcing was varied in the range 10-120 Hz (Chelidze et al., 2005; 2013).

In order to assess the strength of phase synchronization 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 (Figs. 6- 12).

Figs. 6 - 12 shows PDF-s obtained for spring stiffnesses 78.4 N/m, 235.2 N/m, 1705.2 N/m and forcing frequencies 10 Hz, 20 Hz 50 Hz, 80 Hz and 120 Hz at various intensities of forcing (frequency of sensor was 20 Hz).

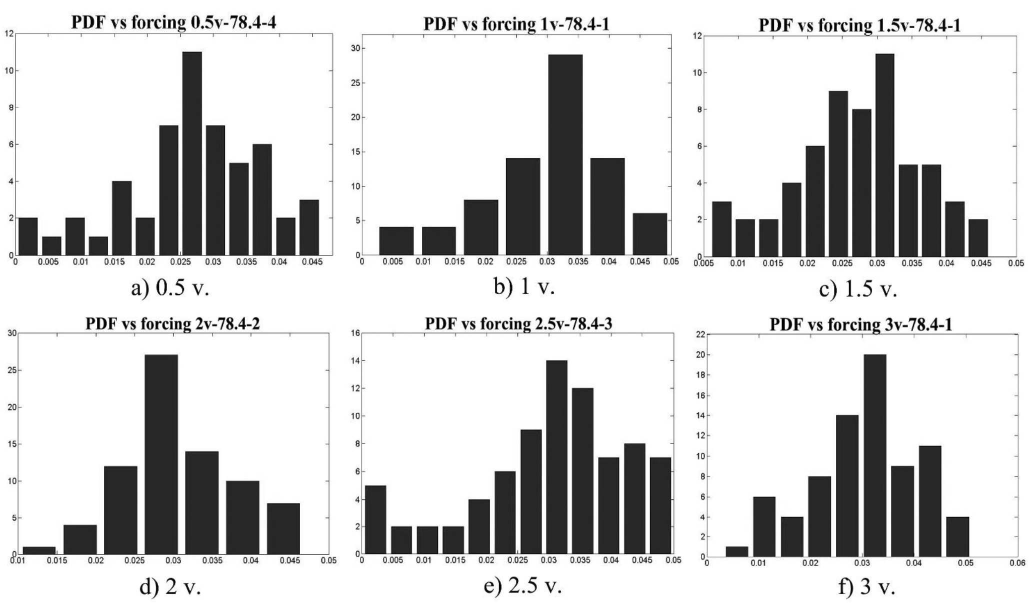


Fig. 6. PDF of number of AE signals at certain phases of forcing (in bins of period) for the stiffness of the spring K_s =78.4 N/m and forcing frequency 20 Hz, which is also a natural frequency of the sensor used. Synchronization at forcing: (a) 0.5 V; (b) 1V; (c) 1.5 V; (d) 2 V; (e) 2.5 V; f) 3 V.

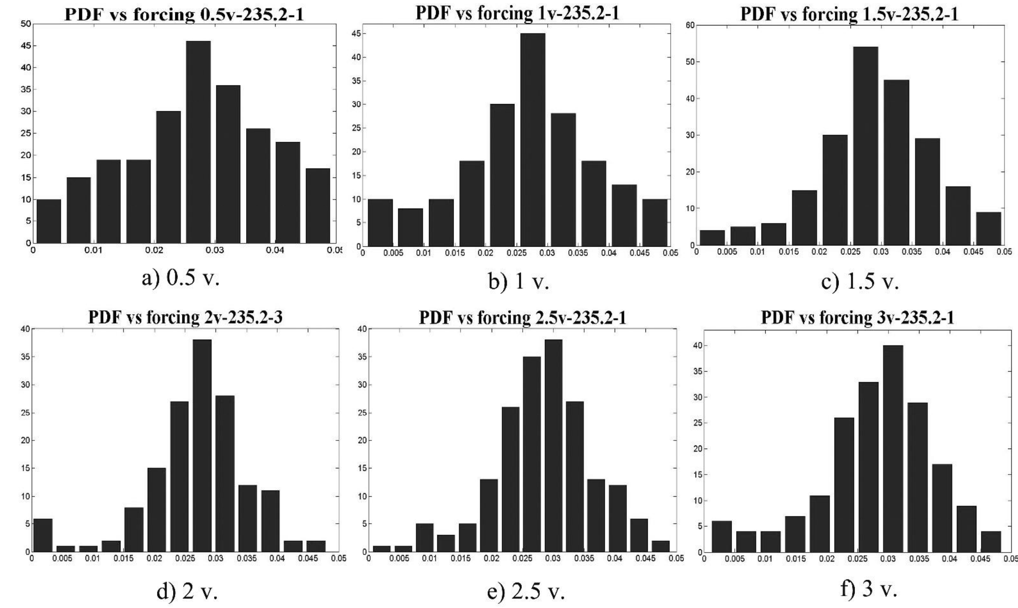


Fig. 7. PDF of number of AE signals at certain phases of forcing (in bins of period) for the stiffness of the spring K_s =235.2 N/m and forcing frequency 20 Hz, which is also a natural frequency of the sensor used. Synchronization at forcing: (a) 0.5 V; (b) 1V; (c) 1.5 V; (d) 2 V; (e) 2.5 V; f) 3 V.

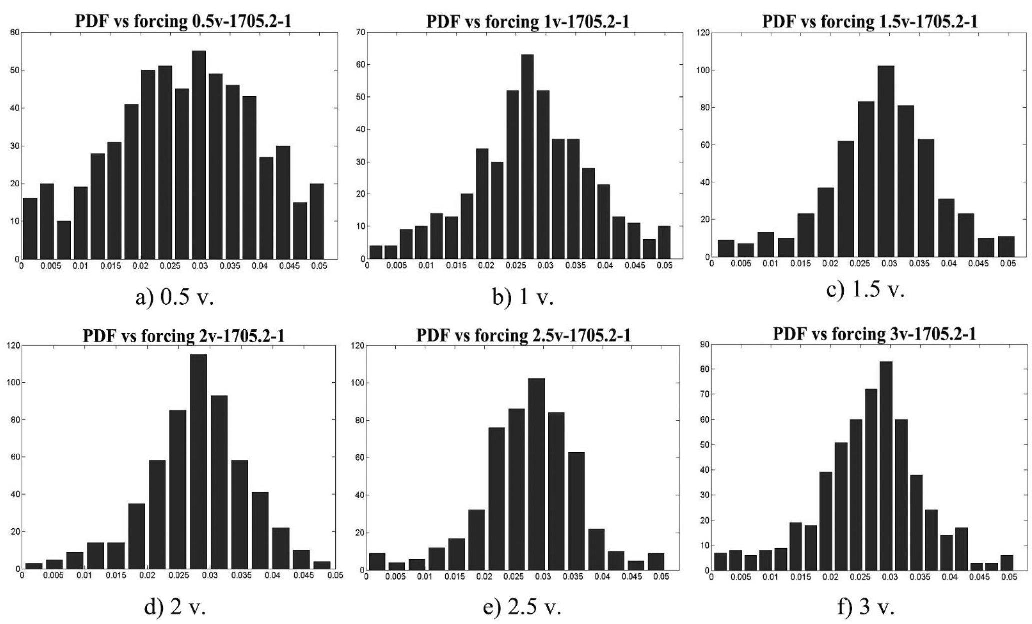
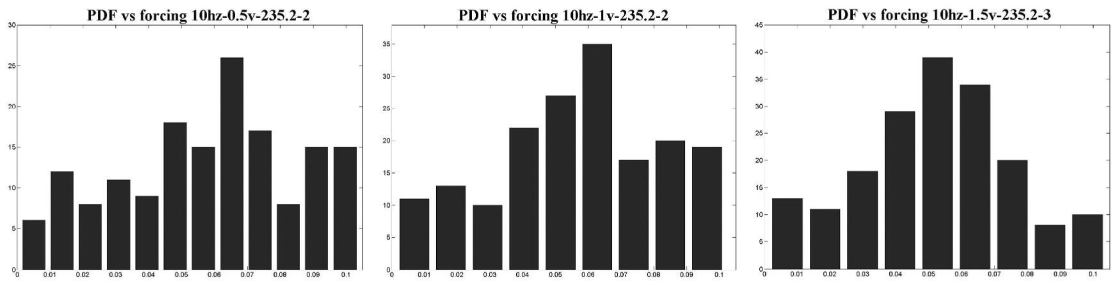
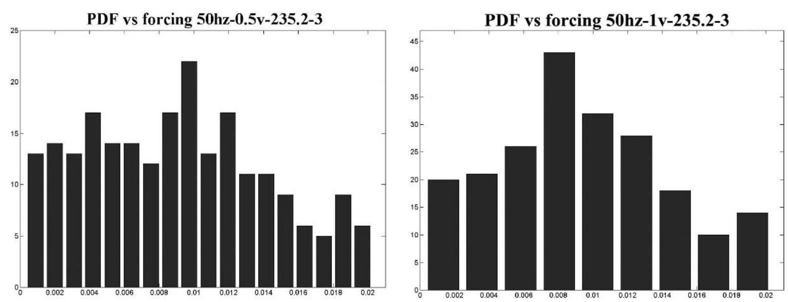


Fig. 8. PDF of number of AE signals at certain phases of forcing (in bins of period) for the stiffness of the spring K_s =1705.2 N/m and forcing frequency 20 Hz, which is also a natural frequency of the sensor used. Synchronization at forcing: (a) 0.5 V; (b) 1V; (c) 1.5 V; (d) 2 V; (e) 2.5 V; f) 3 V.

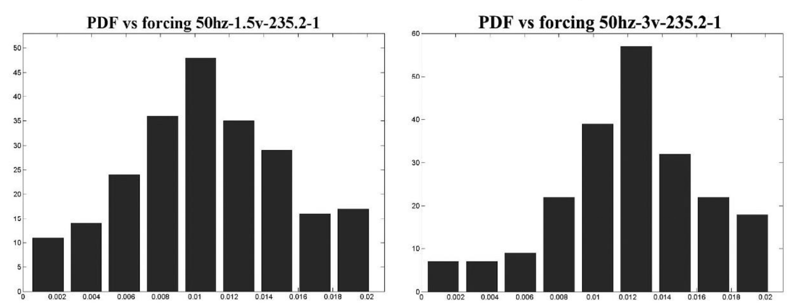


a) 0.5 v. b) 1 v. c) 1.5 v.

Fig. 9. PDF of number of AE signals at certain phases of forcing (in bins of period) for the stiffness of the spring K_s =235.2 N/m and forcing frequency 10 Hz (natural frequency of sensor 20 Hz). Synchronization at forcing: 0.5 V (a); 1V (b); 1.5 V (c).



a) 0.5 v. b) 1 v.



c) 1.5 v. d) 3 v.

Fig. 10. PDF of number of AE signals at certain phases of forcing (in bins of period) for the stiffness of the spring K_s =235.2 N/m and forcing frequency 50 Hz (natural frequency of sensor 20 Hz). Synchronization at forcing: 0.5 V (a); 1V (b); 1.5 V (c); 3 V (d).

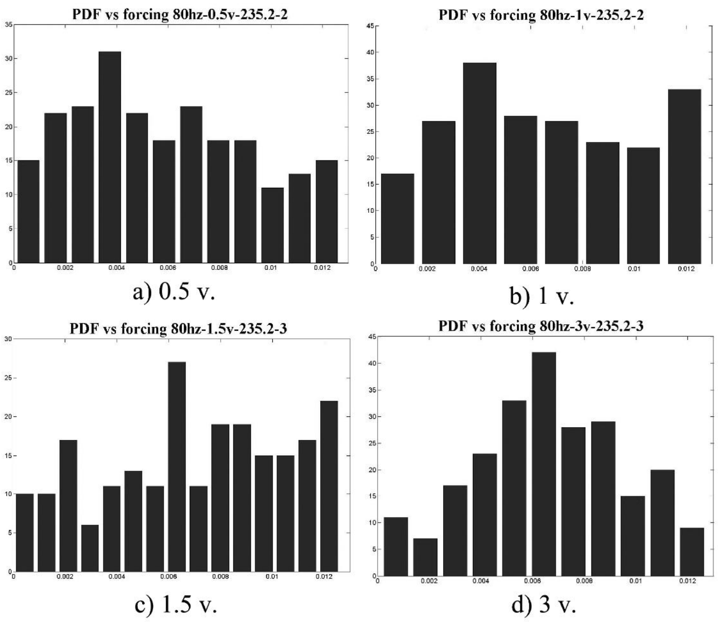


Fig. 11. PDF of number of AE signals at certain phases of forcing (in bins of period) for the stiffness of the spring K_s =235.2 N/m and forcing frequency 80 Hz (natural frequency of sensor 20 Hz). Synchronization at forcing: 0.5 V (a); 1V (b); 1.5 V (c); 3 V (d).

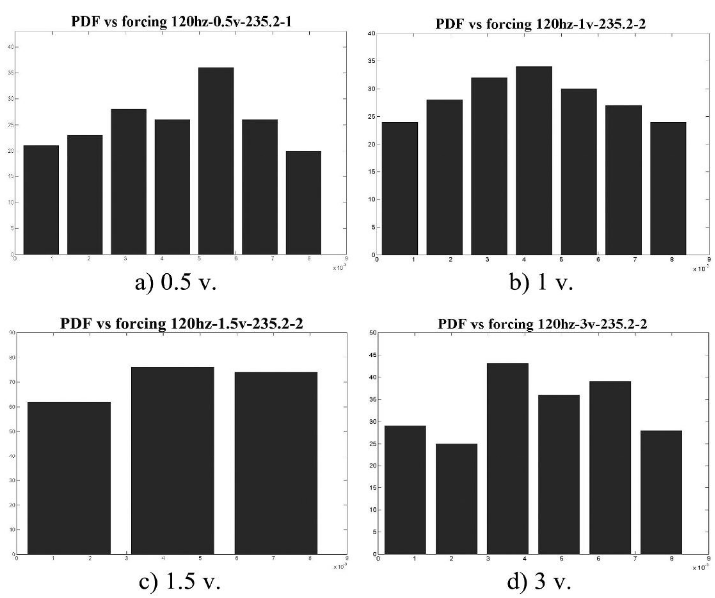


Fig. 12. PDF of number of AE signals at certain phases of forcing (in bins of period) for the stiffness of the spring K_s =235.2 N/m and forcing frequency 120 Hz (natural frequency of sensor 20 Hz). Synchronization at forcing: 0.5 V (a); 1V (b); 1.5 V (c); 3 V (d).

Arnold's tongue for mechanical forcing.

For randomly distributed AE signals such PDF plots are almost flat and for increased strength of synchronization are bell curve like with the half-width $(W/2)$ 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.13). Here synchronization strength is assessed visually from PDFs in Fig. 7, Figs. 9-12 for spring stiffness K_s =235.2 N/m. 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 40-50 Hz, which is close enough to 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.

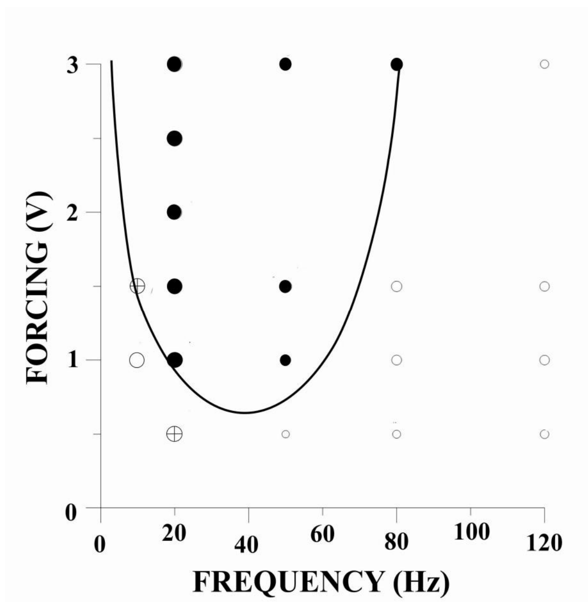


Fig.13. Phase space plot of synchronization strength dependence on intensity and frequency of forcing or Arnold's plot. Synchronization strength was assessed visually from PDFs in Figs.9-12 for the spring stiffness K_s =235.2 N/m. Hollow dots mean absence, dots with crosses – moderate and filled dots – good synchronization.

Conclusions

In the paper, the results of laboratory experiments on the mechanical or electromagnetic synchronization of mechanical instability (slip) of a slider-spring system are presented. Slip events were recorded as acoustic emission bursts. The data allow delineating approximately of 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 close enough to 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 etc) in both EM and mechanical synchronization experiments.

Acknowledgements
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Языки Арнольда при электромагнитной и механической синхронизации (Stick-slip)

Т. Челидзе, Е. Мепаридзе, Д. Тепнадзе

Резюме

Явление синхронизации встречается в различных процессах, в механике, биологических и социальных процессах. Таким образом, вполне естественно, что синхронизация наблюдается во многих геофизических сферах, поскольку Земля находится под влиянием колебательных процессов (форсинга) различного происхождения с чрезвычайно широким диапазоном частот, от нескольких секунд до нескольких месяцев и лет. Такие крупномасштабные природные процессы могут быть смоделированы в лабораторных условиях.

В данной работе представлены результаты лабораторных экспериментов при механической и электромагнитной синхронизации нестабильности при неустойчивом трении (стик-слипе) системы. Механические нестабильности были записаны как всплески акустической эмиссии. Данные позволяют приблизительно ограничивать области синхронизации (языки Арнольда) на графике интенсивность форсинга-частота форсинга при механической и электромагнитной синхронизации.