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Dynamical features of acoustic emission of natural and forced stick-slip process

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Abstract. Friction processes, including stick-slip movement, are regarded as complex phenomenons of mass and energy transfer between two surfaces through elastic and inelastic interactions of macroscopic, micro and nano contacts. Such processes can be observed in different natural and technical systems and are subject of intense interdisciplinary investigations. For example, stick-slip motion as a model of earthquake generation, which is often analyzed for last decades. Acoustic emission (AE) accompanying the stick-slip process is a sensitive tool for revealing fine details of the complex friction process. In the present work, AE accompanying the stick-slip movement of basalt samples are investigated in laboratory slider-spring device under different experimental conditions, including weak mechanical or electromagnetic forcing of various intensity and frequency. Recurrence quantification analysis and Lempel and Ziv complexity measure methods have been used to assess changes occurred under external forcing in time series of stick-slip AE process.
Keywords: Friction processes, Stick-slip movement, Acoustic emission, External forcing, Recurrence, Complexity measure, Complex dynamics.

1 Introduction

It is known, that wherever two surfaces move against each other frictional resistance occur. This causes the wear – damage to a solid frictional surfaces involving progressive loss of material (Czichos *et al.*[11]). In general, friction is regarded as a complex phenomenon of mass and energy transfer between two surfaces through elastic and inelastic interactions of macroscopic, micro and nano contacts (Persson[29]). Having dual, energy transmitting and dissipating role, processes contributing to the friction have a wide range of spatio-temporal scales and they act through different mechanisms. At the nano and micro scales, corresponding to distances between atoms in solids, friction acts as a dissipation factor converting kinetic to the thermal energy. At longer length scales, the dual roles of friction, energy transmitting and dissipating, almost always coexist. The conditions under which friction provides (transmits) more energy to system than

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that can dissipate constitute the basis for most of instabilities observed in friction-excited movement regimes (vibrations, stick slip, etc.). In turn these instabilities contribute to wearing process of contacting surface materials.

According to present understanding, tribological response of material i.e. friction and wear, do not only represent intrinsic material properties but depend on conditions of contacting surfaces, as well as on the motion character (Demirel and Granick[12],Braiman *et al.*[5], Urbakh*et al.*[39],Czichos *et al.*[11]). We can distinguish dry friction-like behavior at low driving velocity and lubricated-like behavior at higher driving velocities. The low velocity regime is characterized by chaotic stick-slip motion, which is basically determined by the interplay between static and kinetic friction forces (Demirel and Granick[12], Rozman *et al.*[31], Matcharashvili *et al.*[25]). For high velocities, the system displays smooth sliding, which resembles thinning of the effective viscosity. Both low- and high-velocity friction regimes depend on the mechanical properties of the system and are separated by a well defined critical driving velocity (Demirel and Granick[12], Urbakh *et al.*[39]).

Ubiquity of friction in natural and technical systems, calls for the further investigation of different types of friction including stick-slip movement.

For geophysicists investigation of stick-slip movement acquires special importance because it is regarded as model os earthquake generation process. Exactly, W. Brace and J. Byerlee in 1966 suggested the relevant physical mechanism - the unstable friction or stick-slip, which explains practically all main features of natural seismic process. In general, first frictional models of seismic process were based on the Griffiths-Irvin concept of linear fracture mechanics of solids (Griffiths[16], Irwin[18]): as this approach is focused on the isolated crack growth under external stress, it mainly can be applied to analysis of the main rupture development. One of the main deficiencies of mechanical fracture models is a lack of cyclicity (recurrence) property, characteristic for the seismic process.

In present research we analyzed AE data sets recorded from laboratory spring-block set up. AE data sets have been recorded at different movement regimes and weak external influences. Such analysis provides interesting information on dynamics of seismic process.

2 Laboratory set up of stick slip experiments

Usually, experimental analyses of the friction regularities have been carried out on three main systems: traditional slider-spring arrangement (Nasuno[27]), biaxial (Marone[23]), three-axial shearing apparatus (Beeler and Lockner[3]) and rotary systems. Depending on conditions (spring stiffness, velocity of drag, normal stress, slip surface state), three main types of friction are observed by displacement recording – stick-slip, inertial regime and quasi-stable regime. Stick-slip regime is observed at relatively low velocities of movement and at low stiffness. At higher velocity the transition to inertial periodic oscillations occurs; furtherwe have the stable sliding with small fluctuations. It is known that the mean period of stick-slip recurrence depends on the drive velocity and spring stiffness, (Nasuno[27]).

The sophisticated methods of recording/analysing acoustic emission, which accompany stick-slip, add important information on the microphysics of the process (Johnson *et al.*[20]). Probably, the main experimental data on friction micro-physics, obtained last decades due to using new technologies, is the discovery of three/four displacement-time scales in the friction dynamics: in addition to early recognized slow (accumulation) and fast (discharge) phases, the so-called precursory or ultra-fast micro-scale displacements and corresponding micro-acoustic signals were discovered (Johnson *et al.*[20]). AE amplitudes for the fast and precursory events are accordingly $5\cdot10^{-7}$ and $5\cdot10^{-9}$ strains and the corresponding waiting times 10^{-1} and $5\cdot10^{-4}$ s (approximately) according to (Johnson *et al*.[20])experiments. The precursory events appear, when the system is close to the critical (discharge) state and disappear immediately after discharge.

Since a seminal paper of (Brace and Byerly[4])and several main succeeding works (Burrige and Knopoff[6],Dietrich[13,14], Ruina[32]), the stick-slip is considered as a main mechanism, explaining the earthquake process and existence of the seismic cycles (Scholz[34,35]). Here we have to note that a half-century before (Brace and Byerly[4], Reid[30]) formulated the elastic-rebound theory, where he considered seismic cycles as the sequence of recurrent (sudden) releases of elastic strain energy, which slowly accumulated in the preceding period, i.e. conceptually, as the integrate-and-fire process.

In our earlier works, for laboratory study of forced stick-slip, the same experimental schemes were used as in the natural stick-slip studies, with addition of weak forcing source. Despite versatile stress application schemes, realized in the two-and three-axial devices, the simple uniaxial system also has its merit, namely, it is free from massive inertial loading frames, which can complicate interpretation of results. This scheme of experiments on mechanical and electromagnetic forcing of stick-slip had many times described in earlier publications (e.g. Chelidze and Lursmanashvili[8], Chelidze and Matcharashvili[9], Chelidze *et al.*[7,10]).

In this work, we analyzed AE data sets recorded from the laboratory set up which represents a system of two horizontally oriented saw-cut basalt plates. The height of surface asperities was in the range 0.1-0.2 mm. A constant pulling force F of the order of several N was applied to the upper (sliding) plate; in addition, the same plate was subjected to periodic mechanical perturbations (forcing) from vibrator. The normal load was constant and equal to the weight of the sliding sample (700 g). In our experiments were varied: i) the frequency of superimposed periodical mechanical perturbation; ii) the amplitude of the external mechanical excitation (forcing); iii) the stiffness of the spring, (78 *N/m*< K_s <1700 *N/m*). The forcing with a variable frequency (from 1 to 120 Hz) and amplitude was applied normal to the slip plane. Mechanical pull from the forcing was much weaker compared to the pulling force of the spring. The mechanical forcing strength was varied by applying voltage from to a mechanical vibrator. Slip events in experiments were registered as acoustic bursts by the sound card of PC (Chelidze and Lursmanashvili[8]). In case of electromagnetis forcing, the spring-block system was the same. Difference was that periodic forcing, periodic electric perturbations with variable amplitude, was applied directly to electrodes, glued to the external surfaces of sliding and fixed blocks.

3 Used methods of data analysis

Our main goal was to analyse dynamical properties of experimental AE time series. In general, natural processes are complex (Rundle *et al.*[33]) mainly due to their nonlinearity, an intrinsic property of the underlying laws, conditioning the absence of determinism of universe. This property (complexity) incorporates phenomena with a very broad diversity of dynamical features. Generally, this diversity manifests itself in a certain kind of hierarchy of dynamical patterns ranging from strict determinism to total randomness. The most important is that between these extremes there are many intermediate states that reveal different degree of orderliness such e.g. periodicity, quasi-periodicity, deterministic chaos, low and high dimensional dynamics, hyperchaos etc. (Kantz and Schreiber[21]). The fundamental problem is how to measure the complexity from the observed time series (Matcharashvili and Chelidze[24]). One of the most often used approach is based on time delay phase space reconstruction of original time series (Takens[37], Sprott[36]). After phase space reconstruction, often it is possible the recurrence features of phase space trajectories, of the considered process, be analysed using different qualitative and quantitative methods: (e.g. Packard *et al.*[28], Takens[37], Abarbanel and Tsimring[1], Kantz and Schreiber[21], Sprott[36]).

Though methods based on phase space reconstruction are very popular, it should be added that besides of phase space testing there are also other tests for complex data analysis, namely, information statistics methods. which allow derivation of the information content (or lack of it) i.e. assessing underlying regularity in a data set. One often use Lempel-Ziv complexity (LZC) measure (Lempel and Ziv[22]), mutual information (Sprott[36]), Shannon and Tsallis entropies (Tsallis[38],Vallianatos *et al.*[40]), etc.

In present research, we used two of above mentioned methods. First, we aimed to carry out Lempel and Ziv algorithmic complexity (LZC) calculation (Lempel and Ziv[22], Aboy *et al.*[2],Hu *et al.*[17]), on AE data sets. LZC is common method for quantification of the extent of order (or randomness) in data sets of different origin. LZC is based on the transformation of analyzed sequence into new symbolic sequence. For this original data are converted into a 0, 1, sequence by comparing to certain threshold value (usually median of the original data set). Once the symbolic sequence is obtained, it is parsed to obtain distinct words, and the words are encoded. Denoting the length of the encoded sequence for those words, the LZ complexity can be defined as

$$C_{LZ} = \frac{L(n)}{n}$$

where *L(n)* is the length of the encoded sequence and *n* is the total length of sequence (Hu*et al.*[17]).

In addition to LZC in the present research, we aimed to carry out the assessment of changes in the dynamical structure of AE data sets by recurrence quantification analysis (RQA) approach (Zbilut and Webber[45], Webber and Zbilut[41],Marwan *et al.*[26]). RQA is often used for analysis different type of data sets. In general, RQA is a quantitative extension of Recurrent Plot (RP) construction method, which is based on the fact that returns (recurrence) to the certain system condition or state space location is a fundamental property of any dynamical system with quantifiable extent of determinism in underlying laws (Eckman *et al.*[15]). In order to successfully fulfill RQA calculations, at first the phase space trajectory should be reconstructed from the given scalar data sets, the proximity of points of the phase trajectory should be tested and marked by the condition that the distance between them is less than a specified threshold ε (Eckman *et al.*[15]). In this way, two-dimensional representation of the recurrence features of dynamics, embedded in a high-dimensional phase space can be obtained. Then a small-scale structure of recurrence plots can be quantified (Zbilut and Webber[45], Webber and Zbilut[41,42],Marwan *et al.*[26], Webber *et al.*[43], Webber and Marwan[44]). RQA technique quantifies visual features in a $N \times N$ distance matrix recurrence plot and defines several measures of complexity. Exactly, RQA provides several measures of complexity based on the quantification of diagonally and vertically oriented lines in the recurrence plot. In this research we calculated one of such measures: the percent determinism (%DET), which is defined as the fraction of recurrence points that form diagonal lines of recurrence plots and shows changes in the extent of determinism in the analyzed data sets.

It is reasonable to assume that the existence of some determinism (i.e. recurrence of definite states) in the structure of above mentioned forced system, is dependent on the forcing intensity/frequency what will change dynamical characteristics of stick-slip AE process.

4 Results and discussion

We have carried out series of experiments for different values of stiffness of driving spring (235, 555 and 1700 N/m) in the frequency range 0.5-120 Hz for different voltages applied to a vibrator, (which in this case is a proxy of mechanical forcing intensity). Typical view of stick slip AE signal recordings is presented in Fig.1.

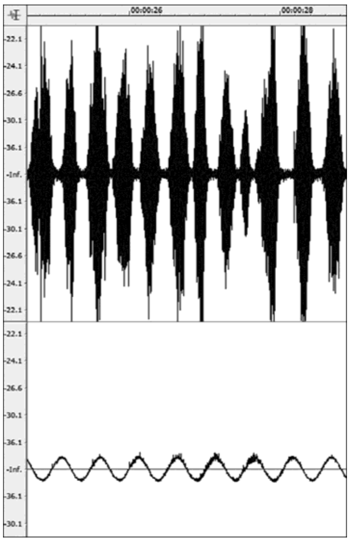


Fig. 1. Typical graph of AE of forced stick-slip. Upper channel - acoustic bursts generated by slips; lower channel – forcing signal.

At low values of spring stiffness and drive voltage we observed so called natural stick slip. In experiments with a spring of stiffness $K_s = 555\ N/m$ and drive velocity 8.47 mm/sec we were able to observe change in dynamical features of AE process. The recurrence period of slips during natural stick-slip process was 0.37 s; correspondingly, the recurrence frequency was 2.7 Hz. The so called 1:1 synchronization was fixed at the forcing frequencies, close to the natural slip frequency, in the range 2-3 Hz. For each frequency and intensity of forcing three sets of experiments were carried out and then merged into one file in order to have sufficient for statistical analysis data set. The experimental time series of phase differences between forcing signal and slip initiation (AE start) were picked up in seconds, then they were converted into $2\pi(Rad)$ units and corresponding histograms were compiled.

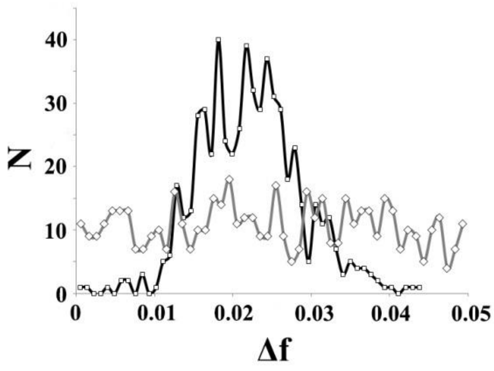


Fig. 2. Typical histograms of natural (grey) and forced (black) stick-slip wave onsets.

In general close to uniform distributions in Fig. 2, does not mean that the recurrence is absent in the case of natural stick-slip. Here the phases of slips are not synchronized with the forcing frequency and thus dynamical features of stick-slip process have not been changed. As a result, phase differences between forcing signal and slips are distributed almost uniformly.

For stick-slip AE signal recordings of natural (without forcing), 20Hz, 40Hz and 80Hz with applied voltage 1V for driving spring stiffness 235 N/m was calculated Lempel-Ziv complexity (LZC) measure and histogram is presented in Fig.3.

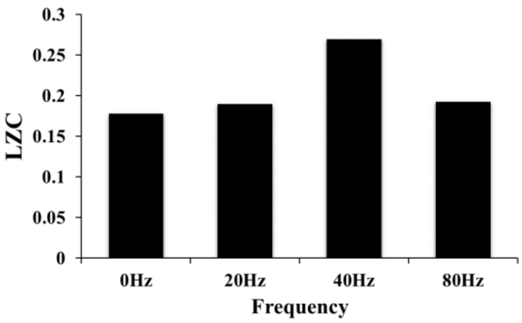
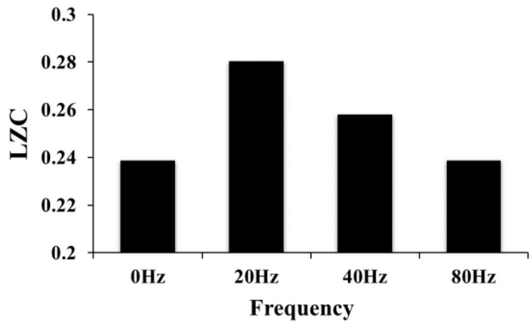
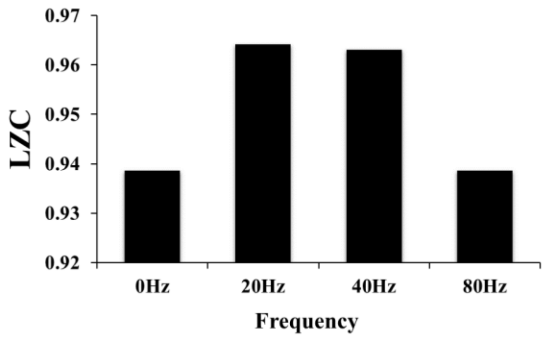


Fig. 3. Lempel-Ziv complexity (LZC) of AE signal recordings of natural (without forcing), 20Hz, 40Hz and 80Hz with applied voltage 1V.

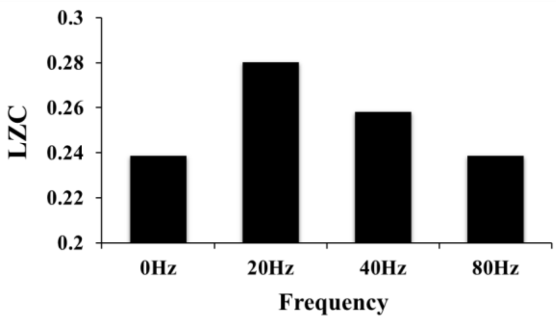
Stick-slip AE signal recordings were filtered. After filtering, the record parameters and according AE signal recordings Lempel-Ziv complexity (LZC) were calculated. On Fig. 4 are shown Lempel-Ziv complexity (LZC) measures histograms of AE signal recordings of natural (without forcing), at 20Hz, 40Hz and 80Hz and applied voltage 1V.



a.



b.



c.

Fig. 4. Lempel-Ziv complexity (LZC) of AE signal recordings of natural (without forcing), 20Hz, 40Hz and 80Hz with applied voltage 1V, a) coordinate of abs. max in AE burst ;b) the distance (number of points) between the end and maximum of AE burst; c) coordinate of onset in AE burst.

At the same time when external forcing increases we observed quantitative changes in dynamics of stick-slip AE process. Indeed, we see in Fig. 5, that percent of determinism, one of the main RQA characteristics, increase at certain external forcing.

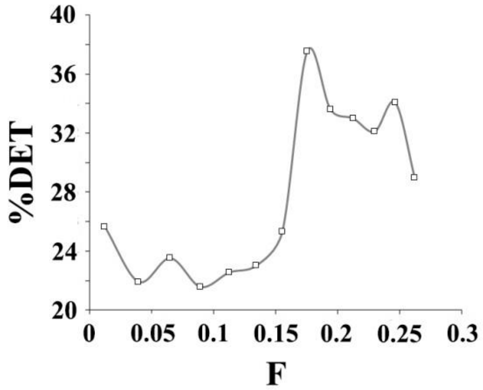


Fig. 5. RQA %DET measures of AE time series of stick-slip process under different external forcings.

Above results and the increase of weak external forcing leads to the dynamical changes of stick-slip process. This was very important because strong increase of forcing could lead to unwanted avoid modulation effects. Such results expand our knowledge about the features of complex frictional process. More over in the light of known facts on the controlling effects of small influences on the dynamics of complex process, our results provides additional arguments in favor that such control through series of small influences may be possible also for the process of strong earthquakes preparation.

Conclusions

Here we present the results of analysis of AE data sets recorded from slider-spring laboratory set up of stick-slip process under mechanical and electromagnetic periodic forcing. External force evokes the phase change in dynamical features of stick-slip process. Acoustic emission bursts were used as the markers of slip events.

We show that weak changes in the forcing frequency and drag velocity may lead to changes in dynamical regime of stick slip process. This is important in the context of possible control of local seismic process trough series of weak external influences.

The results, obtained by our analysis can be important both in seismology and in stick-slip tribology.

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