Synchronization of stick-slip acoustic emission caused by small influences

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Abstract: We investigated dynamics of acoustic emission, accompanying stick-slip motion of sample rocks and influence of small external impacts on its features. For that, laboratory spring-slider system has been developed enabling registration of acoustic emission (AE) related to stick-slip at different sliding regime and relative external forcing. Series of time intervals between consecutive waveforms of AE and its maximums have been analyzed. To create these time series, experimental recordings were conditioned, wave trains separated and onsets of the AE detected. For quantitative evaluation of changes in dynamics of acoustic wave generation, nonlinear recurrence quantitative analysis (RQA) and phase synchronization testing procedures have been used. Analysis was carried out for three sliding regimes as well as weak normal forcing up to 30 % relative to applied dragging force. It was shown, that extent of deterministic structure in dynamics of acoustic wave generation depends on movement regime. Moreover, external forcing up to 25% relative to dragging force may synchronize phase of stick-slip motion, what leads to increase of extent of order in dynamics of AE.

Keywords: Synchronization, Stick-slip, Acoustic emission, Nonlinear dynamics, Recurrent analysis.

1. Introduction

In this research we aimed to investigate dynamical characteristics of nonlinear stick-slip frictional system through analysis of accompanying emission of acoustic waves.

It is known that the friction develops between sliding surfaces and results in transmission and dissipation of energy of relative motion. At the same time, frictional processes are not always stationary and at constant drive rates stick-slip oscillations may occur. Stick-slip inherently suggests instability and represents intermittent motion when the stress builds up to a threshold value, then when the friction pumps to the system more energy than can be dissipated by the stationary process stress is rapidly released [2]. When stress suddenly changes the part of stored strain energy is released in the form of elastic waves, including ones with sonic frequencies [1, 4]; it is important to mention that the reverse effects are also observed, namely, elastic waves from vibrations can affect the friction [1, 5]. Thus one of the most fundamental aspects of stick-slip friction, is an AE process that involves oscillations of atoms.
Elastic waves generation related to stick-slip oscillations often are observed and investigated in spring-slider systems. Spring-slider systems are not less interesting from geophysical point of view too, because are considered as a proxy of geological faults under tectonic stress. Hence dynamical aspects of acoustic wave generation in spring-slider systems is the object of intense research in geophysics, seismology and tectonics [3, 11, 17]. Furthermore, nonlinear spring-slider systems can be used to investigate the phenomenon of anomalously high sensitivity to small changes regarded as physical mechanism underlying complex dynamics. Thus we aimed to investigate the character of influence of weak external impacts on dynamics of AE in nonlinear spring-slider system. Besides their general scientific value such analysis may help in understanding of controlling and triggering phenomena taking place in complex systems: e.g. induced seismicity, earthquake triggering, synchronization etc. [9, 10, 14]. At the same time, results of analysis of dynamics of elastic wave generation in a spring-slider system as well as influence of small external impacts on acoustic wave generation will be interesting also for a fundamental friction science, as far as they indicate to some intimate details of investigated process in stick-slip regime.

2. Methods
Experimental spring-slider of our stick-slip AE experiments represents a system of two horizontally oriented plates of the same roughly finished basalt. The height of surface protuberances was in the range 0.1-0.2 mm. A constant pulling force in the range of 4-10 N was applied to the upper (sliding) plate. In order to investigate influence of weak external impacts on dynamics of a stick-slip AE, the same plate was subjected to periodic mechanical or electric perturbations with variable frequency. Further details of our experiment are given in Chelidze et al, 2003, 2005 [7, 8].

![Figure 1. Sample AE recordings after wave trains separation.](image)

Experimental recordings from laboratory system have been conditioned, filtered and wave trains separated (see Figure 1).
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Then onsets of the AE signals have been detected [6, 12], and series of time intervals between consecutive AE bursts (\(\Delta tAE\)) and between AE maximums (\(\Delta tAE_{max}\)) have been created.

3. Results and discussion

To investigate dynamical properties of accompanying stick-slip acoustic waves emission and assess its deterministic structure the method of RQA [13, 18] has been used. In Figure 2, results of the RQA statistics called % determinism (%DET) are presented. After, in order to quantify tiny changes in dynamics of investigated process we have calculated quantitative measures of strength of synchronization between weak external forcing and stick-slip AE. For this, the analytic signal concept, based on the Hilbert transform [15] was used and phase differences calculated. Then, mean effective phase diffusion coefficient and phase synchronization measure (\(\gamma H-Sh\)) of phase differences between AE and external forcing intensity were calculated [16].

![Figure 2. RQA %DET measures of \(\Delta tAE\) (dotted curves) and \(\Delta tAE_{max}\) (continuous curves) time series vs. relative external forcing](image)

It was shown that, without forcing, RQA %DET measure of analyzed time series increases from 18 to 27 when driving force rises (spring becomes twice stiffer). Thus dynamics of stick-slip AE depends on dragging regime and at certain conditions reveal more deterministic structure.

According to the phase synchronization testing, as slopes of phase differences evolution between stick slip AE and relative force of external influence decrease, the measure \(\gamma H-Sh\) increases. This points to the phase synchronization of stick-slip process by small imposed impacts. Indeed, RQA characteristics show increase of amount of deterministic structure (Figure 2) in \(\Delta tAE\) and \(\Delta tAE_{max}\) time series when relative force of external influence rises to about 20%. This means that small external influences lead to the
increase of order of dynamics in acoustic wave generation during nonlinear process of stick slip process.

4. Conclusions
Our analysis show that dynamics of acoustic wave temporal distribution depends on sliding regime and can be modified through weak external forcing. It was demonstrated in laboratory experiments, that dynamics of complex process (stick-slip) can be quantitatively modified by small periodic impacts. These results are important to clear up possible controlling effects of external small/moderate periodic forcing on the temporal behaviour of complex dynamical systems (including seismic process), as well as from the general elastic wave generation points of view.

References
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