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Geophysics

The Dependence of the Forced Stick-Slip Waiting Times on the Forcing Frequency and Intensity

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ABSTRACT. The laboratory stick-slip process, forced by a weak periodical mechanical vibration, is a small-scale model of the triggering/synchronization of the large-scale mechanical instabilities (earthquakes). The natural stick-slip can be considered as a relaxation process, which manifests a quasi-periodic sequence of slow (stick phase, when the stress is accumulating) and fast (stress-drops or slip events) phases. The stick-slip process is non-linear and thus, it is highly sensitive even to a weak external forcing. In the paper we studied the effect of weak mechanical periodic forcing on the phase synchronization of the slip occurrence: in this way we try to study laboratory model of seismic activity synchronization by Earth tides. We studied the dependence of a number of forcing oscillations and waiting times between successive slips on the forcing frequency. The experiments show that forced stick-slip waiting times are minimal at forcing frequencies, corresponding to the minimum of synchronization area (so-called Arnold's tongue minimum) in the phase plot of forcing intensity versus forcing frequency. The present results evidence that the natural waiting time T_0 for recurrence of slips in a given system decreases significantly under periodic mechanical forcing in the 30-40 Hz range. Possibly, in this way we can find the optimal frequency for sick-slip stabilization and consequently, minimization of friction, which is an important problem in tribology. *© 2017 Bull. Georg. Natl. Acad. Sci.*

Key words: Catalog, stick-slip, waiting times, triggering

The natural stick-slip can be considered as a relaxation process, which manifests a quasi-periodic sequence of slow (stick phase, when the stress is accumulating) and fast (stress-drops or slip events) phases. This process actually corresponds to an autonomous oscillator with a natural frequency ω_0. Exposure of such autonomous oscillator to a weak forcing of frequency ω and intensity I changes its natural frequency ω_0 to some different value Ω [1]. Corresponding definitions in terms of periods are: natural period - T_0; forcing period - T; observed period after application of forcing - T_{obs}. The difference $(\omega - \omega_0)$ is called detuning. On the plot of I versus ω, the so called Arnold's plot [2], the detuning is minimal at the point, where the forcing frequency is close to the natural frequency of oscillator; as the detuning increases, you need stronger forcing and at very large detuning synchronization becomes im-

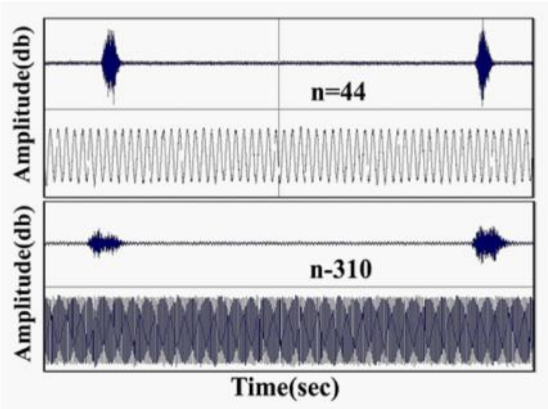

Fig. 1. The number of periods n between successive slips at two frequencies: (upper plot) for forcing frequency 10 Hz and intensity 0.5V, n=44; (lower plot) the same for 120 Hz and 0.5V, n=310.

possible. There are several kinds of synchronization between oscillating system with natural frequency μ_0 and forcing of frequency μ. We are looking for the phase synchronization (PS) when amplitudes are irregular and uncorrelated, but the frequencies μ and Ω are adjusted. There is a regular phase shift between μ and Ω. As a rule, at mechanical forcing we observed high-order phase synchronization (HOS), when slips occur after m forcing periods, as in Fig.1 [3-5]. High-order synchronization means that the forcing (μ) and observed (Ω) frequencies in the system are related to each other by the relation $n\mu = m\Omega$ [1].

Experimental Setup

Experimental set up represents a system of two plates of roughly finished basalt (with average height of surface asperities of 0.1–0.2 mm). A constant dragging force of order of 10N was applied to the upper (sliding) plate weighing 0.7 kg; in addition, the system was subjected to periodic mechanical perturbations with variable amplitude and frequency. The mechanical forcing was much weaker (of order of 10^{-3}- 10^{-4} N) compared to the driving (spring) force (of the order of 10 N). Slip events were recorded as acoustic emission bursts. Acoustic emission waveforms as well as the sinusoidal mechanical forcing signal were digitized at 48 kHz. Details of the setup and technique are given in [6,7]. Experiments were carried out at an ambient air humidity 20-40%.

Methodology/Theory

There are many papers devoted to the problem of a forced stick-slip [8-14]. In some of them it was found that the higher is the forcing frequency the larger is the number of oscillation periods before the induced slip; in other words, the lower is forcing frequency, the less number of periods is needed to initiate slip (Fig. 1).

In the present paper we try to find systematically, if really more oscillations are needed to induce slip at a higher forcing frequencies and if so, does this mean that more time is needed to initiate slip at high forcing frequencies. Besides, we try to establish, if there is an optimal forcing frequency and intensity for a phase synchronization [1,15,16] of mechanical instabilities, which can affect (shorten of increase) the natural waiting time (or natural period) T_0 between consecutive slips during stick-slip motion. For this, we counted the number of periods between consecutive slips as well as the waiting times at various intensity and frequency of forcing.

Results and Discussion

The experiments were carried out on horizontal spring-slider model for forcing frequencies in the range 10-120 Hz and three various intensities, corresponding to the input voltage on mechanical vibrator 0.5V, 1.0V and 3.0V. We looked for the connection of the slips in the stick-slip motion with the periodic mechanical forcing signal. We counted the number of periods m between onsets of successive acoustic emission bursts (slips) at various forcing frequencies μ and find that m increases systematically with the increase of μ at all intensities (Fig. 2 a, b, c) with a small kink at 30-40 Hz, which will be discussed later on. We will define the winding ratio as a number of forcing periods during one period of autonomous oscillator W=1 : m, where m in general can be equal, larger or less than 1 (W=1 corresponds to 1:1 synchronization). Fig. 2 shows that one acoustic pulse

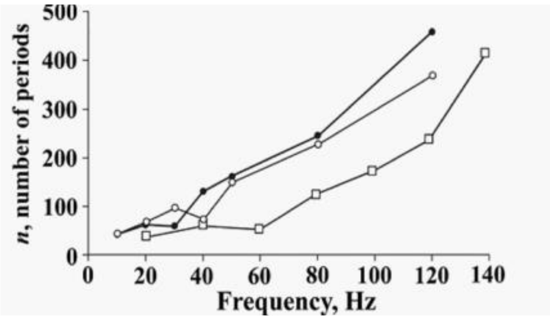

Fig. 2. The number of periods *n* between onsets of successive acoustic emission bursts (slips) versus forcing frequencies (Hz) at the input voltage on the vibrator 0.5V (line with black dots), 1.0V (line with white squares), 3.0V (line with white dots).

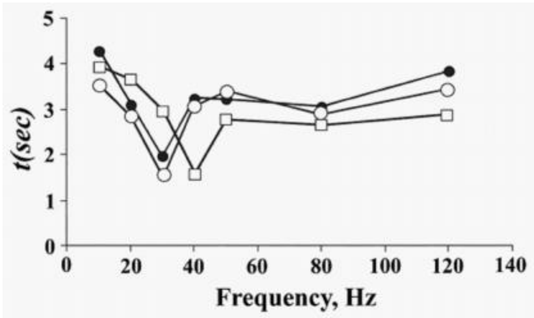

Fig. 3. The waiting time *t* (sec) between the onsets of slip versus forcing frequency (Hz) at the input voltage on the vibrator 0.5V (line with black dots), 1.0V (line with white dots), 3.0V (line with white squares).

is generated after each (approximately) 44 forcing periods at forcing frequency 10 Hz, accordingly, $W = 1:44 = 0.023$. At forcing frequency 120 Hz one acoustic pulse is generated after each (approximately) 310 forcing periods, so the $W = 1:310 = 0.0032$. The *W* decreases at high frequency of forcing.

The low values of winding number, obtained in our experiments, should be characteristic of the forcing frequency range, used in our experiments. According to [17], forced stick-slip regime changes radically at low frequencies: at forcing frequency $\mu = 0.14$ Hz during one forcing period occur 6 slips, so the winding number is larger than 1, namely, at $\mu \approx 0.14$ Hz the *W* value is 1:0.17= 5. 88, but at forcing frequency $\mu = 0.01$ Hz during one forcing period 12 slips occur and $W = 1:(1/12) = 1:0.08 = 12.5$. Taking into account the data of Savage (2007), the transition from $W > 1$ to $W < 1$ regime should take place at a forcing frequency ≈ 0.1 Hz.

It is interesting to note that the periodic electric forcing, applied to the identical spring-slider system (basalt blocks), also invokes HOS with a winding ratio depending on the forcing stile: *W* varies from 1:1 synchronization (*W*=1) to a HOS with *W*>1 at low frequencies of forcing [3, 4, 7].

We also tried to find, if the change of *W* means that the waiting time *t* between the onsets of slip also vary. On the Fig. 3 (a, b, c) we plot the waiting times between slip onsets, corresponding to the experimental conditions of Fig. 2 (a, b, c). It is evident that the waiting time *t* between successive slips is almost constant (3-4 sec) at all forcing frequencies and intensities, except a repetitive drop to 1.5-2 sec at frequencies 30-40 Hz. The dominant waiting times $t = 3-4$ sec are evidently connected with a natural period of non-forced (and accordingly, non-synchronized) stick-slip.

We conclude that despite strong increase of oscillation number *n* between slip onsets with rising forcing frequency, the waiting times between recurrent slips do not change significantly in the wide range of forcing frequencies. Exactly, forcing changes the natural period T_0 of the stick-slip to $T_{obs} < T_0$ only in a narrow frequency range 20-40 Hz, where the forcing results in a strong drop of the waiting times. The systematic drop of the waiting times *t* at forcing frequencies 20-40 Hz (or in other words, acceleration of the slip occurrence), can be explained by the existence of the so called Arnold's tongue in the phase space plot of synchronization strength at various frequencies and intensities of forcing [18]. The Arnold's tongue delineates synchronization area on the phase plot of forcing intensity *I* versus forcing frequency μ and has a reverse bell-plot form with a minimum at the optimal *I* and μ. At this point, the detuning $(\mu - \mu_0)$ is minimal, i.e. forcing frequency is close to the natural frequency of oscillator, which causes shortening of observed waiting times from $T_0 = 3-4$ sec to $T_{obs} = 1.5-2$ sec. Indeed, in stick-slip experiments, carried out in identical conditions with the present research [18], it is shown that the lowest forcing intensity for synchronization onset corresponds to 30-40 Hz, which means that in given conditions the friction resistance is minimal. The present results evidence that besides minimization of forcing intensity at the Arnold's tongue minimum, the natural waiting time T_0 for recurrence of slips in a given system also decreases significantly in the 30-40 Hz range at any used intensity of forcing, (i.e. in the synchronization area). In other words, only due to the phase synchronization, very weak external forcing can significantly affect (shorten) waiting times of recurrent slips in a spring-slider system, which is driven by a much stronger force. That points to possibility of optimal forcing frequency detection, which can be interesting for applied tribology problems, namely, for friction resistance reduction/stabilization during stick-slip motion [19]. Besides, the study is informative for the earth sciences, namely, for a research of earthquake triggering/synchronization by weak natural (tides, seasonal forces, teleseismic waves from remote strong earthquakes) or manmade forcing (reservoir load-unload).

Conclusions

The experiments on the stick-slip under by weak periodic mechanical forcing were carried out on a nonlinear system (horizontal spring-slider model) for forcing frequencies in the range of 10-120 Hz and various forcing intensities. We found that the mechanical forcing in the mentioned frequency range, as a rule, evoked a winding ratio $W<1$. The present results evidence that the natural waiting time T_0 for recurrence of slips in a given system decreases significantly under periodic mechanical forcing in the 30-40 Hz range, i.e. in the maximal phase synchronization area (at the Arnold's tongue minimum). The low values of winding number, obtained in our experiments (W from 0.023 to 0.0032) should be characteristic of the used frequency range. According to other authors' data forced stick-slip regime changes radically at low frequencies of the order of 0.01 Hz, where the winding ratio increases and becomes larger than 1. Transition from $W<1$ to $W>1$ should take place at ≈ 0.1 Hz.

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გეოფიზიკა

სტიქ-სლიპის მოლოდინის დროების დამოკიდებულება ფორსინგის სიხშირესა და ინტენსივობაზე

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პერიოდული სუსტი მექანიკური ზემოქმედებით გამოწვეული სტიქ-სლიპის (დაყოვნება-დაცურების) პროცესი წარმოადგენს დიდმასშტაბიან მექანიკური არამდგრადობების (მიწისძვრების) ტრიგირირებისა/სინქრონიზაციის მოდელს. ბუნებრივი სტიქ-სლიპი შეიძლება განვიხილოთ როგორც რელაქსაციის პროცესი, რომელიც ნელი (სტიქ-ფაზა, დაძაბულობის დაგროვება) და სწრაფი (დაძაბულობის განმუხტვა ან სლიპ-მოვლენა) ფაზების კვაზიპერიოდულ თანმიმდევრობას ავლენს.

სტიქ-სლიპი არაწრფივი პროცესია და სუსტ გარეშე ზემოქმედებების მიმართ ძალზე მგრძნობიარეა. ნაშრომში შევისწავლეთ ხახუნის დროს სუსტი მექანიკური პერიოდული ზემოქმედების (ფორსინგის) გამო წარმოქმნილი ფაზური სინქრონიზაციის ეფექტი. ასეთი მიდგომით ჩვენ ვეცადეთ შეგვესწავლა დედამიწის მიმოქცევებით გამოწვეული სეისმური აქტივობის სინქრონიზაციის ეფექტი ლაბორატორულ მოდელზე. ჩვენ შევისწავლეთ ფორსინგის ოსცილაციების რიცხვის და დაცურებებს შორის მოლოდინის დროების დამოკიდებულება ფორსინგის სიხშირეზე. ჩატარებული ექსპერიმენტებიდან ჩანს, რომ სტიქ-სლიპ პროცესის მოლოდინის დროები მინიმალურია მოდებული ფორსინგის იმ სიხშირეზე, რომელიც სიხშირის და ინტენსივობის ფაზურ დიაგრამაზე შეესაბამება სინქრონიზაციის არეს (ე.წ. არნოლდის ენის მინიმუმს). წარმოდგენილი შედეგები ადასტურებენ, რომ მოცემულ სისტემაში 30-40 ჰც პერიოდიული მექანიკური ზემოქმედება მნიშვნელოვნად ამცირებს დაცურების ბუნებრივი მოლოდინის დროს T_0. ამ გზით ჩვენ შეგვიძლია ავარჩიოთ ოპტიმალური სიხშირე სტიქ-სლიპ პროცესის სტაბილიზაციისათვის და შესაბამისად ხახუნის შემცირებისათვის, რაც ტრიბოლოგიის მნიშვნელოვან პრობლემას წარმოადგენს.

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