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Influence of Correlated Coloured Noises on an Underdamped Josephson Junction

I.A. Knyaz' *

Sumy State University, 2, Rymsky-Korsakov St., 40007 Sumy, Ukraine

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The paper describes a non-trivial effect of realization of the electrical transport in a stochastic model of Josephson junction due to correlated colored noises. It is shown that the cross-correlation plays an important role: by controlling the correlation between the thermal and external noises, a reversal for the net voltage can be induced. It is shown that the behavior of the dc voltage versus the dc current can be manipulated by controlling the noise intensities and strength of cross-correlation. At zero dc current the strength of cross-correlations plays a role of control parameter; an increase in this parameter leads to voltage growth. Frequency content of noises is a critical parameter at small noise intensity: a reversal for the voltage can be realized by controlling the auto- and cross-correlation times of thermal and external noises. It is found that correlated noises promote the occurrence of negative conductance at small positive values of dc bias. At the same time the voltage does not assume the opposite sign of the dc bias at negative values of one due to cross-correlation between noises. It is shown that an increase in noise strength at a small friction coefficient leads to regimes which correspond to a normal, Ohmic-like transport behavior. The dependence of the voltage versus the amplitude of the ac current at small positive dc bias depicts a quasiperiodic series of windows of noise-induced anomalous regimes: negative conductance appears and disappears as the ac-amplitude strength increases.

Keywords: Directed transport, Colored noises, Cross-correlation, Josephson junction.

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1. INTRODUCTION

As known, nonequilibrium fluctuations and disturbed spatial symmetry are sufficient conditions for the implementation of particle transfer mechanism. Recently, such problems have raised interest in terms of modern mass separation techniques, applications in biological transport, approaches to the creation of superconducting contacts, description of the flows of magnetic phases in SQUID and chemical reagents in the configurations of molecules [1].

Among the wide spectrum of mentioned problems the development of theoretical foundation of the noise-induced electrical transport in Josephson junctions can be picked out [2-7]. Earliest theoretical investigations of superconductor junctions predicted the appearance of net voltage and dc voltage rectification due to influence of asymmetric noise. Afterwards, it was reported that the delta-correlated additive and multiplicative white noises can also produce a net voltage even at zero dc and ac currents [2]. In the paper [3] a driven, resistively and capacitively shunted Josephson junction device was investigated. In the framework of numerical simulations the various regimes of anomalous transport behavior, such as absolute negative conductance, negative differential conductance and negative-valued nonlinear conductance were discovered. It was shown that the thermal fluctuations play a key role in these processes. Noise-induced bifurcations in the underdamped and overdamped models of Josephson junctions were investigated in the works [4, 5]. It was found that an increase in autocorrelation rate of a colored noise leads to the monostability-bistability transitions and noise-enhanced stability. Noise-induced transitions in a current-biased and weakly damped Josephson junction with dc bias source under the influence of multiplicative noise were investigated in [6]. It was shown that in such systems a stochastic Hopf bifurcation between an absorbing and an oscillatory states occurs. In paper [7], the effect of both Gaussian and Lévy flights fluctuations on the ballistic graphene-based small Josephson junctions is explored. Authors showed that the noise enables to get the probability distribution of the passages to finite voltage from the superconducting state as a function of the bias current.

For today, of special interest are anomalous transport phenomena in the presence of external and thermal correlated noises. In paper [8], we have shown that the correlation between coloured multiplicative and additive noises is the reason of realization of directed transport in the symmetrical periodic systems. We will now address the questions which naturally arise. First, does the anomalous transport take place under the influence of more realistic coloured noises, and, second, what is the role of spectral characteristics of noises in the processes of electrical transport in Josephson junctions?

In order to answer these questions in the present work the Stewart-McCumber model is investigated. We will generalize the model by inclusion of color noise, which describes the environmental perturbation, and consider both an unbiased and a current-biased Josephson junctions.

2. MODEL

We explain the dynamics of the Josephson junction in terms of the well-known Stewart-McCumber model, which describes the dynamics of the phase difference $\phi(t)$ across a junction [3]:

* knigorua1@gmail.com

$$\left(\frac{\hbar}{2e}\right)^2 C\ddot{\phi}+\left(\frac{\hbar}{2e}\right)^2\frac{1}{R}\dot{\phi}+\left(\frac{\hbar}{2e}\right)I_0\sin\phi= \\ =\left(\frac{\hbar}{2e}\right)I_d+\left(\frac{\hbar}{2e}\right)I_a\cos(\Omega t)+\left(\frac{\hbar}{2e}\right)\sqrt{\frac{2k_BT}{R}}\eta(t), \quad (1)$$

where I_0 is the critical current, R is the resistance, C is the capacitance, k_B is the Boltzmann constant, T is the temperature of the system. The dot denotes differentiation with respect to time t, I_d and I_a are the amplitudes of the applied dc and ac currents, respectively, Ω is the angular frequency of the ac driving source. The thermal equilibrium fluctuations are modeled by color noise $\eta(t)$.

In the case of the environmental perturbation, such as the perturbation of the external electromagnetic fields, the change of the external temperature and so on, the internal structure of the Josephson junction should change. These perturbations lead to variation of the critical electric current. So, we should replace I_0 by $I_0+\zeta(t)$, where $\zeta(t)$ is color noise.

Let us suppose the noises to be Gaussian distributed with zero mean, colored in time according to the correlation function:

$$C_{\mu,\nu}(t-t')=\langle\mu(t)\nu(t')\rangle=\kappa\frac{\sigma_\mu\sigma_{\bar{\nu}}}{\tau_{\mu,\nu}}\exp\left(-\frac{|t-t'|}{\tau_{\mu,\nu}}\right), \quad (2)$$

where $\tau_{\mu,\nu}$ are the correlation times; σ_μ are the strengths of noise ($\mu,\nu=\{\zeta,\eta\}$); κ is the strength of the cross-correlation of the two noises ($k=1$ if $\mu=\nu$).

The dimensionless form of this equation takes the form:

$$\ddot{\phi}+\gamma\dot{\phi}+\sin\phi=i+j\cos(\Omega' t')+\zeta'(t')\sin\phi+\eta'(t'), \quad (3)$$

where $\gamma=\tau/RC$ is the friction coefficient; the dot denotes differentiation with respect to the dimensionless time $t'=t/\tau=\omega_0 t$; $\omega_0=\sqrt{2eI_0/\hbar C}$ is the plasma frequency; $\eta'(t')$ and $\zeta'(t')$ are the rescaled thermal and external noises, respectively. The intensities of noises: $\sigma'_\eta=\sigma_\eta\sqrt{\gamma/E_J}=\sqrt{2\gamma k_BT/E_J}$ ($E_J=(\hbar/2e)I_0$ is the Josephson coupling energy), $\sigma'_\zeta=\sigma_\zeta/E_J$. The amplitude and the angular frequency of the ac are $i=I_a/I_0$ and $\Omega'=\Omega\tau$, respectively. The rescaled dc reads $j=I_d/I_0$. Further we will omit the prime for the sake of simplicity.

The most important characteristic for the above system is the stationary dimensionless averaged voltage which reads

$$\bar{U}=\left\langle\dot{\phi}\right\rangle_s, \quad (4)$$

where the brackets denote an average over the initial conditions, over all realizations of the noises and a temporal average over one cycle of the external ac-driving.

3. ANALYTICAL ANALYSIS

In work [9], we presented a formalism that makes it possible to obtain the stationary equation for the probability density for a class of models of stochastic dissipative systems with a nonlinear coefficient of friction in the presence of an inertial component of evolution and statistically dependent fluctuations. We will apply the developed approach (details in [9]) for analytical analysis of the model (3). For that, it is convenient to rewrite Eq. (3) in the form

$$\ddot{\phi}+\gamma\dot{\phi}=f(\phi)+\sum_\mu g_\mu(\phi)\zeta_\mu, \quad (5)$$

where $f(\phi)=-(\partial/\partial\phi)V=-\sin\phi+i+j\cos(\Omega' t')$, $g_\zeta=\sin\phi$, $g_\eta=1$, $\mu=\{\zeta,\eta\}$, V is the potential. To apply our approach we should simplify the model (5) by assuming $j=0$ (the case $j\neq 0$ will be considered later in the framework of numerical simulations only). As a result, the Fokker-Planck equation reads

$$\frac{\partial P}{\partial t}=-\frac{\partial}{\partial\phi}J(\phi,t), \quad (6)$$

where

$$J(\phi,t)=D_1(\phi)P(\phi,t)-\frac{\partial}{\partial\phi}\left[D_2(\phi)P(\phi,t)\right] \quad (7)$$

is the probability current. The expressions for the effective drift and diffusion coefficients take the form

$$D_1=\frac{\sin(\phi)-i+\kappa\tau_{\eta,\zeta}\sigma_\eta\sigma_\zeta\cos(\phi)+\tau_\zeta\sigma_\zeta^2\sin(\phi)\cos(\phi)}{\gamma}, \\ D_2=\frac{\sigma_\eta^2+2\kappa\sigma_\eta\sigma_\zeta\sin(\phi)+\sigma_\zeta^2\sin^2(\phi)}{\gamma^2}. \quad (8)$$

In the stationary case:

$$t\to\infty,\ J(\phi,t)=J=const,\ P(\phi,t)\to P.$$

Analytical expression for J can be obtained for the case $i=0$ (the case $i\neq 0$ will be considered later in the framework of numerical simulations only). In that case, as it follows from (3), the potential is described by a symmetric periodic function, $V(\phi)=V(\phi+L)$, where $L=2\pi$. Hence the stationary probability density $P(\phi)$ will also be periodic, $P(\phi)=P(\phi+L)$, and Eq. (6) in the stationary case may be solved within an interval [0, L]. The expression for the probability current in the case of a periodic potential and a symmetrical multiplicative function reads [8]:

$$J=\frac{1-e^{-\int_0^{2\pi}D_1(\phi)/D_2(\phi)d\phi}}{\int_0^{2\pi}e^{-V_{ef}(\phi)}\int_\phi^{\phi+2\pi}D_2^{-1}(\phi')e^{V_{ef}(\phi')}d\phi'd\phi}, \quad (9)$$

where

$$V_{ef}(\phi)=\ln D_2(\phi)-\int_0^\phi\frac{D_1(\phi')}{D_2(\phi')}d\phi'. \quad (10)$$

The magnitude J allows us to obtain the stationary average velocity [10]:

$$\langle\dot{\phi}\rangle_s=LJ, \quad (11)$$

where L is the spatial period.

It follows from Eq. (8) that $D_1(L-\phi)=-D_1(\phi)$, $D_2(L-\phi)=D_2(\phi)$ at $\kappa = 0$ (no cross-correlation). So, the numerator in (10) is equal to zero (no voltage, $\bar{U}=0$). So, in the unbiased model the only reason for the appearance of voltage is the cross-correlation between internal and external noises. The same situation arises in the case of absence of external noise ($\sigma_\zeta = 0$): the Second Law of Thermodynamics is not violated (internal fluctuations can not be transformed into work).

4. RESULTS

In Fig. 1 and Fig. 2 we plot the voltage U versus the intensity of external noise σ_ζ and thermal noise σ_η at $i = j = 0$. Some characteristic features can been seen from the figures: (a) the voltage is a nonmonotonic function of the noise strength and it is always negative; (b) the curves for the voltage as a function of noise intensities have extremes, which is the reverse of the manifestation of resonance; (c) with increase in the friction coefficient γ the valley value of the curve for U ascends, while with increase in the strength of the cross-correlation κ the valley value descends. From Fig.1, one can observe that with decrease in the intensity of thermal noise σ_η the valley value moves to the left. As seen from Fig. 2, the correlation time τ_ζ plays an insignificant role at large enough values of noise intensity and leads to amplification of voltage at small values of the latter one (with increase in τ_ζ).

To verify the correctness of the analytical results we need to perform numerical simulations of equation (3). To obtain many-dimensional random process with correlation matrix defined from (2), we will be based on the Ornstein-Uhlenbeck process. The numerical integration of the original model equations was performed by using the Euler procedure. Generation of correlated random processes $\zeta(t)$ and $\eta(t)$ is performed in accordance with the algorithm used in our work [8]. The time-discrete numerical data are calculated with the integration step of $\Delta t = 0.001$. Initial conditions for $\phi, \dot{\phi}, \zeta$ and η were chosen randomly from a uniform distribution in the interval [− 0.5, 0.5]. We define the rescaled voltage by averaging over an ensemble of K randomly chosen initial conditions for the average voltage (4):

$$\bar{U} = \frac{1}{N}\frac{1}{K}\sum_{i=1}^{N}\sum_{j=1}^{K}\dot{\phi}_j(t_i),$$

where N is the discrete set of time points t_i, uniformly distributed in the time interval $t \in [600, 1500]$. Every point in the figures is calculated by taking the average of the $K = 300$ initial conditions and the $N = 10^4$ different discrete times. To ensure that the system has reached a stationary state, the first $5 \cdot 10^4$ steps were discarded. From Fig. 1 and Fig. 2 we can see that numerical simulations qualitatively confirm the results which were predicted by analytical approach.

The influence of cross-correlation parameter $\tau_{\eta,\zeta}$ on the value of U is shown in Fig. 3. Since the proposed analytical approach was built for a case of small correlation times, the analytical results for a case $\tau_{\eta,\zeta} > 1$

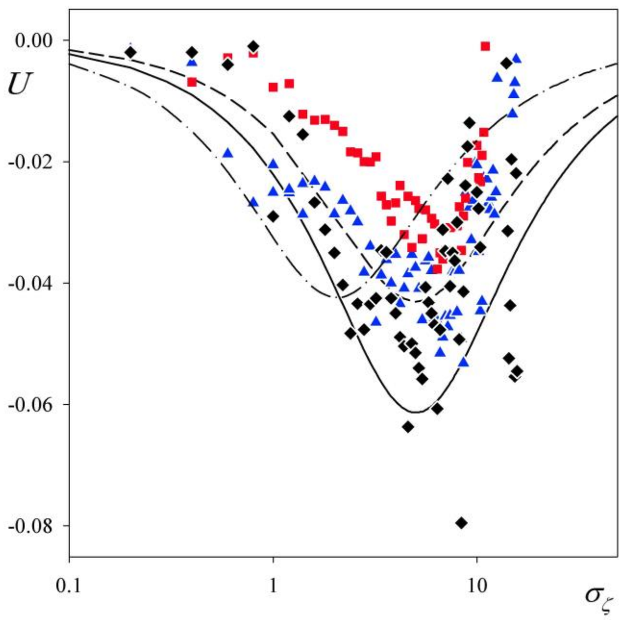

Fig. 1 – The voltage $U = \bar{U}/2\pi$ of superconducting junction vs noise intensity of external noise σ_ζ according to analytical approach and numerical simulations (symbols) at $i = 0$, $j = 0$, $\kappa = 0.5$, $\tau_{\eta,\zeta} = \tau_\eta = \tau_\zeta = 0.1$. Values of the parameters: $\gamma = 0.7$, $\sigma_\eta = 5.0$ (solid lines and black diamonds); $\gamma = 1.0$, $\sigma_\eta = 5.0$ (dashed-line curve and blue triangles); $\gamma = 1.0$, $\sigma_\eta = 2.0$ (dash-dot line and red rectangle)

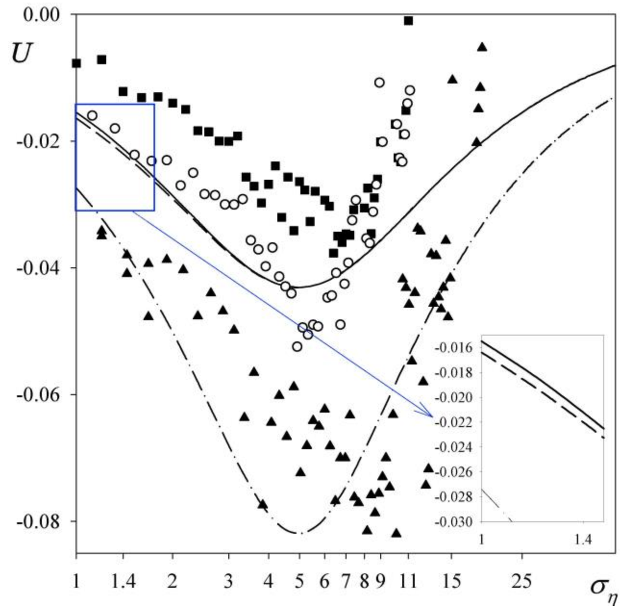

Fig. 2 – The voltage $U = \bar{U}/2\pi$ of superconducting junction vs noise intensity of thermal noise σ_η according to analytical approach and numerical simulations (symbols) at $i = 0$, $j = 0$, $\gamma = 1.0$, $\tau_{\eta,\zeta} = \tau_\eta = 0.1$, $\sigma_\zeta = 5.0$. Values of the parameters: $\kappa = 0.5$, $\tau_\zeta = 0.01$ (solid lines and black rectangles); $\kappa = 0.5$, $\tau_\zeta = 0.1$ (dashed-line curve and white circles); $\kappa = 0.8$, $\tau_\zeta = 0.1$ (dash-dot line and black triangles)

should not be considered as fully regular. But since the numerical results confirm qualitatively the analytical ones we have left them for understanding the basic trend of the system behavior with an increase in $\tau_{\eta,\zeta}$.

From Fig. 3 we can see that the curves for the voltage as a function of cross-correlation times $\tau_{\eta,\zeta}$ have extremes: peak values of U appear at $\tau_{\eta,\zeta} \approx 0.5$. As shown in Fig. 3, the transition to δ-correlated noises leads to a decrease in voltage. It should be noted that with increase in correlation time of external noise τ_ζ the valley value of the curve for U moves to the right.

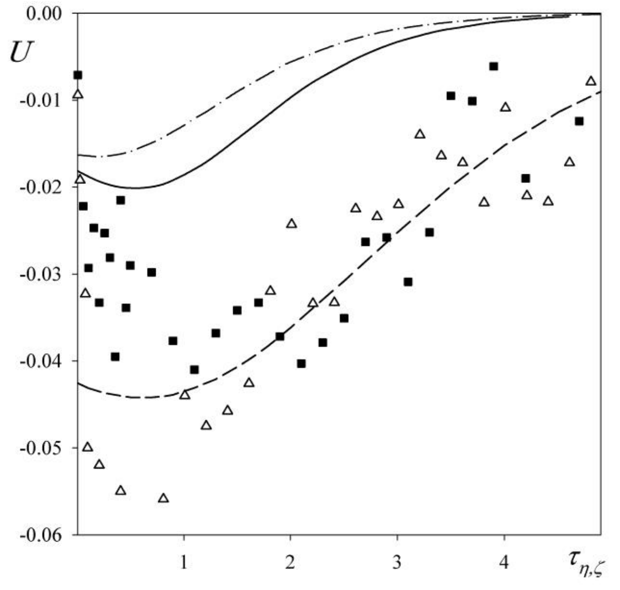

Fig. 3 – The voltage $U = \bar{U}/2\pi$ of superconducting junction vs cross-correlation time $\tau_{\eta,\zeta}$ according to analytical approach and numerical simulations (symbols) at $i = 0$, $j = 0$, $\kappa = 0.5$, $\gamma = 1.0$, $\sigma_\zeta = 2.0$, $\tau_\eta = 0.1$. Values of the parameters: $\tau_\zeta = 0.3$, $\sigma_\eta = 1.0$ (solid lines and black rectangles); $\tau_\zeta = 0.1$, $\sigma_\eta = 5.0$ (dashed-line curve and triangles); $\tau_\zeta = 0.1$, $\sigma_\eta = 1.0$ (dash-dot line)

The most important characteristic for the above system is the current-voltage curve. To obtain it, we numerically integrated Eq. (3) at $i \neq 0$, $j \neq 0$. In this case, as it follows from Eq. (3) the reflection symmetry of the system potential V is broken and a nonzero voltage typically emerges even if cross-correlation parameter $\kappa = 0$. So, the system dynamics will be defined through the joint action of the applied dc and the noise cross-correlation. Since the system dynamics is nonlinear, it should not come as a surprise that some most nonintuitive behaviors still remain to be unraveled.

In Fig. 4, we plot the dependence of the voltage versus the dc current i. As shown in the figure, in the absence of noise a simple step-like behavior of the voltage versus the dc current appears. Shapiro steps are clearly visible. An increase in the intensities of non-correlated noises leads to smoothing of curve $U(i)$. As a result, at small values of friction coefficient a normal, Ohmic-like behavior of the dc voltage is realized.

If the intensity of cross-correlation $\kappa \neq 0$, the effect of negative conductance is realized: at small positive values of current i the voltage is negative (see an inset in Fig. 4). At the same time the presence of noise cross-correlation excludes the possibility of the appearance of positive values of voltage at negative current i.

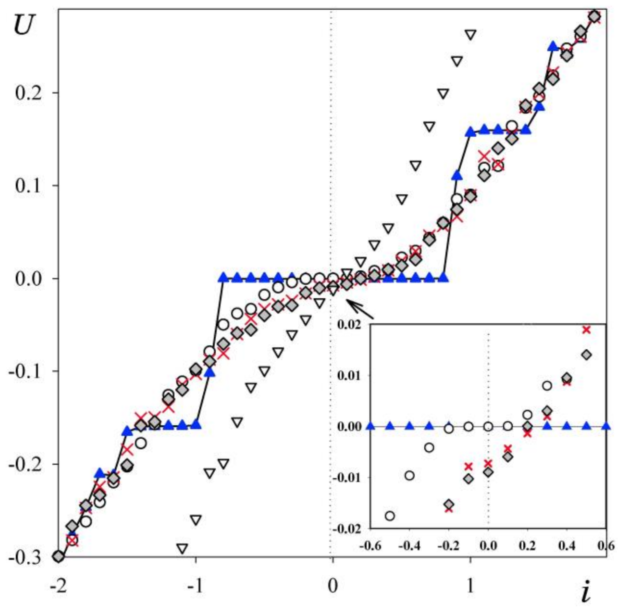

Fig. 4 – The diagram depicts the dependence of the voltage versus the dc current i (i-U characteristic) at $j = 1.0$, $\Omega = 1.0$, $\tau_{\eta,\zeta} = \tau_\eta = \tau_\zeta = 0.1$. Other parameters: $\sigma_\eta = \sigma_\zeta = 0$, $\gamma = 1.0$ (blue triangles); $\kappa = 0.0$, $\gamma = 1.0$, $\sigma_\eta = 1.0$, $\sigma_\zeta = 2.0$ (white circles); $\gamma = 1.0$, $\kappa = 1.0$, $\sigma_\eta = 1.0$, $\sigma_\zeta = 2.0$ (red symbols X); $\gamma = 1.0$, $\kappa = 1.0$, $\sigma_\eta = 2.0$, $\sigma_\zeta = 5.0$ (gray diamonds); $\gamma = 0.5$, $\kappa = 1.0$, $\sigma_\eta = 1.0$, $\sigma_\zeta = 2.0$ (white triangles)

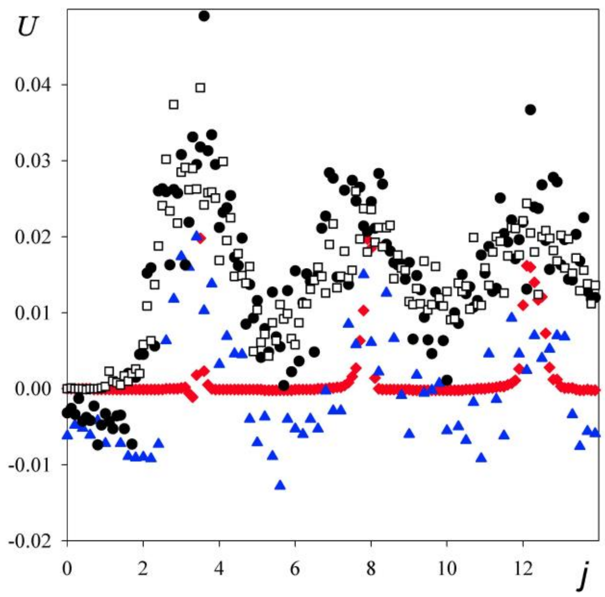

Fig. 5 – The diagram depicts the dependence of the voltage versus the ac current j at $\Omega = 1.0$, $\gamma = 1.0$, $\tau_{\eta,\zeta} = \tau_\eta = \tau_\zeta = 0.1$. Other parameters: $\sigma_\eta = \sigma_\zeta = 0$, $i = 0.1$ (red diamonds); $\sigma_\eta = 1.0$, $\sigma_\zeta = 2.0$, $i = 0.1$, $\kappa = 0.0$ (white rectangles); $\sigma_\eta = 1.0$, $\sigma_\zeta = 2.0$, $i = 0.1$, $\kappa = 1.0$ (black circles); $\sigma_\eta = 1.0$, $\sigma_\zeta = 2.0$, $i = 0.0$, $\kappa = 1.0$ (blue triangles)

From Fig. 4 we note that with the decrease in friction coefficient, the curve for the voltage versus the dc current is nearer and nearer to that for the Ohmic theorem. In this case, all Cooper-pairs get broken and a tunneling process is not possible anymore.

Fig. 5 shows the dependence of the voltage versus the variation of the driving amplitude j of the ac for a positive dc set at $i = 0.1$. Some characteristic features can been seen from the figure: (a) the dependence $U(j)$ is a quasiperiodic function: at the extremum points positive values of voltage are observed; (b) the influence of non-correlated noises leads to an increase in width of ac current domains which correspond to $U > 0$; (c) if the intensity of cross-correlation $\kappa \neq 0$, the effect of negative conductance is realized: the dependence $U(j)$ moves to the negative voltage region. From Fig. 5, one can observe that there exist several parameter windows depicting a noise-induced negative conductance behavior at $i > 0$: the voltage exhibits sign changes multiple times upon increasing the ac-amplitude strength j. Between these negative conductance windows, normal transport regimes occur.

5. CONCLUSIONS

In this work, we have shown that, in a noise-driven Josephson junction, cross-correlated noises can induce nonzero current due to symmetry breaking. Let us summarize the various transport phenomena.

The voltage behavior at zero bias as a function of noise intensity exhibits many familiar features known from the field of Brownian motors, such as the occurrence of a typical bellshaped behavior versus noise strength. In the absence of external bias the voltage is a nonmonotonic function of the noise strength and its absolute value has a clear peak. At zero dc current the strength of cross-correlations κ plays a role of control parameter; an increase in κ leads to voltage growth. Frequency content of noises is a critical parameter at small noise intensity: a reversal for the voltage can be realized by controlling the auto- and cross-correlation times of thermal and external noises. Time of cross-correlation $\tau_{\eta,\zeta}$ plays a nontrivial role: starting from a small nonzero value, the voltage may decrease with increasing $\tau_{\eta,\zeta}$, reaching a negative minimum value. Upon further increasing $\tau_{\eta,\zeta}$, the voltage starts to increase again towards zero.

In the ac- and dc-driven Josephson junctions an increase in noise strength at a small friction coefficient leads to regimes which correspond to a normal, Ohmic-like transport behavior. More interesting and nontrivial are, however, the regimes of anomalous transport: the system exhibits the realization of negative conductance at small positive values of dc bias. At the same time, the voltage does not assume the opposite sign of the dc bias at negative values of one due to cross-correlation between noises. Moreover, the dependence of the voltage versus the amplitude of the ac current at small positive dc bias depicts a quasiperiodic series of windows of noise-induced anomalous regimes: negative conductance appears and disappears as the ac-amplitude strength increases. Between these negative conductance windows, normal transport regimes occur. The effect of negative conductance is realized on conditions that the intensity of cross-correlation $\kappa \neq 0$.

In conclusion, we hope that our results can provide a theoretical foundation for the further investigation of superconducting junctions, especially in experiments.

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Вплив корелюючих кольорових шумів на довгий Джозефсонівський контакт

І.О. Князь

Сумський державний університет, вул. Римського-Корсакова, 2, 40007 Суми, Україна

У роботі описується нетривіальний ефект реалізації електронного транспорту у стохастичній моделі Джозефсонівського контакту за рахунок впливу корелюючи кольорових шумів. Показано, що крос-кореляція відіграє важливу роль: зміна інтенсивності крос-кореляції між тепловим та зовнішнім шумом є причиною реалізації реверсивної поведінки напруги. Показано, що поведінка напруги при зміні сталого струму суттєвим чином залежить від інтенсивності шумів та інтенсивності крос-кореляції. За відсутності сталого струму інтенсивність крос-кореляції відіграє роль керуючого параметра; збільшення даного параметру приводить до зростання напруги на контакті. Спектральний склад шумів відіграє важливу роль при малих інтенсивностях шуму: реверсивна поведінка напруги має місце при зміні часу авто- та крос-кореляції теплового та зовнішнього шумів. Знайдено, що корелюючи шуми є причиною появи від'ємної напруги при малих додатних значеннях сталого струму. У той самий час напруга залишається від'ємною за умови від'ємних значень струму. Показано, що зростання інтенсивності шуму при малих значеннях коефіцієнта дисипації приводить до нормального омічного транспортного режиму. Знайдено, що залежність напруги від амплітуди змінного струму при малих додатних значеннях сталого струму містить квазіперіодичну послідовність областей індукованої шумом аномальної поведінки: від'ємна напруга періодично з'являється та зникає при збільшенні сили змінного струму.

Ключові слова: Спрямований транспорт, Кольорові шуми, Крос-кореляція, Джозефсонівський контакт.