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RELAXATION TIMES AND CORRELATION FUNCTIONS UNDER THE INFLUENCE OF CROSS-CORRELATED COLORED NOISES FOR THE MODEL OF RESONANT TUNNELING

The effects of cross-correlated noises on the process of relaxation of fluctuations in the model of resonant tunneling, in which the noise sources due to incident flow intensity fluctuations and frequency fluctuations are assumed to exist, are considered. To characterize the dynamical behavior of the system, the normalized correlation functions and the associated relaxation times are calculated with the help of a projection-operator technique with regard for memory effects. The influence of noise intensities, their correlation times, and the strength of correlation between the noises on these functions has been analyzed. It is found that the strength of a cross-correlation between two noises can facilitate the intensity fluctuation decay. The behavior of the relaxation time with respect to that of the strength of noises can be characterized as a stochastic resonance phenomenon. It is shown that an enhancement of the self-correlation time of the intensity fluctuations accelerates the transition from the unstable state, while the growth of the self-correlation time of frequency fluctuations results in the retardation of the transition, thereby stabilizing the system.

Keywords: resonant tunneling, intensity correlation function, associated relaxation time, strength of cross-correlation, external colored noises.

1. Introduction

One of the fundamental problems in studies of the dynamics of nonequilibrium systems is the investigation of their behavior under the influence of noises of different nature. It is reasonable to suggest that there can be more than one source of noise in physical systems, for instance, internal thermal fluctuations and external random perturbations. The former are represented usually as an additive term in the Langevin equation and the latter are related to fluctuations of the external parameter as a multiplicative term. In particular, such treatment was justified for laser models [1–4].

In Ref. [5], it was supposed that fluctuations of some parameters can lead to noises of the additive, as well as multiplicative, character, which are not independent. They can have the common origin and, therefore, correlate with one another [5–7]. At the present time, the effects of correlation between noises of different nature are widely investigated within different models [8–11]. In the study of a behavior of unstable systems under the influence of noises, a much attention is paid to the investigation of noises with finite correlation times (colored noises), which allows one to construct, in some cases, a more realistic model for describing the system [4, 10–13].

An important aspect of the dynamical behavior of stochastic systems is the fluctuation decay depending on the system parameters and noises. As the dynamical characteristic of fluctuations in stochastic unstable systems, the correlation functions in a nonequilibrium steady state and the associated relaxation times are often used [4, 8, 10, 12–15].

In the present paper, we study the influence of colored noises of different nature on the process of fluctuation decay in a model system describing the resonant tunneling of electrons in double-barrier nanostructures. It is known that such structures can strongly enhance the transmission coefficient under the resonance condition, which gives opportunity to fabricate resonant tunneling diodes on their base, which have great prospects for their use in various electronic devices [16]. That is why studying the noise effects in such structures in regions of instability is of importance.

In our model of tunneling process [17], the instability takes place during the transition from the state with low tunneling effectiveness to the state with high one. In Refs. [18, 19, 21], we have considered the influence of white noise on the dynamics of this system. In Ref. [20], the influence of colored noise on a mean first passage time close to an instability point has been investigated. In Ref. [21], the problem of mutual influence of the amplitude and phase noises in the incident electron flow on the correlation function of the outgoing flow intensity has been considered by means of the linearization of the evolution equations. In this work, we investigate how the considered tunneling system is affected by the noise caused by fluctuations in the incident flow intensity and by the noise originated from random violations of the resonant frequency detuning. We assume that both noises have finite correlation times and can correlate with each other. The dynamical behavior of the system under the influence of these noises will be described with the help of the correlation function of the outgoing flow intensity and the associated relaxation time.

In Sec. 2, the general expressions used in the calculation of the correlation functions and the associated relaxation times are given. The stochastic model under consideration is represented in Sec. 3. Sec. 4 contains the calculations of the correlation functions and the relaxation times. Conclusions are given in Sec. 5.

2. Correlation Function and Associated Relaxation Time

The general Langevin equation with two noise sources can be written as

$$\dot{x} = f(x) + g_1(x)p(t) + g_2(x)q(t), \tag{1}$$

where $f(x)$ is the deterministic term of a nonlinear process, and $p(t)$ and $q(t)$ are Gaussian colored noises with zero mean $\langle p(t)\rangle = \langle q(t)\rangle = 0$, and the correlation functions

$$\langle p(t)p(t')\rangle = \frac{D}{\tau_1}\exp(|t-t'|/\tau_1),$$

$$\langle q(t)q(t')\rangle = \frac{Q}{\tau_2}\exp(|t-t'|/\tau_2),$$

$$\langle p(t)q(t')\rangle = \langle q(t)p(t')\rangle \frac{\lambda\sqrt{DQ}}{\tau_0}\exp(|t-t'|/\tau_0).$$

Here, D and Q are noise intensities, $g_1(x)$ and $g_2(x)$ are, in the general case, nonlinear functions of x, τ_1 and τ_2 are self-correlation times of two noises, respectively, τ_0 is the time of their mutual cross-correlation, and $0 \le \lambda \le 1$ defines the correlation strength between these noises.

The approximate Fokker–Planck equation corresponding to Eq. (1) with the use of Novikov's theorem [22] and Fox's approximation [2] is given by the expression [7, 11]

$$\frac{\partial P(x,t)}{\partial t} = -\frac{\partial}{\partial x}A(x)P(x,t) + \frac{\partial^2}{\partial x^2}B(x)P(x,t), \tag{2}$$

where

$$A(x) = f(x) + G'(x)G(x) \quad \text{and} \quad B(x) = [G(x)]^2,$$

$G(x)$ with regard for the self-correlation times of noise components and their cross-correlation time for small correlation times can be written as [6, 10, 11, 23]

$$G(x) = \left[\frac{D}{1+a\tau_1}[g_1(x)]^2 + \frac{2\lambda\sqrt{DQ}}{1+a\tau_0}g_1(x)g_2(x) + \right.$$
$$\left. + \frac{Q}{1+a\tau_2}[g_2(x)]^2\right]^{1/2}$$

with $a = -f'(x)$ (index $'$ stands for the derivative with respect to x). The stationary probability density is given by

$$P_{\rm st} = \frac{N}{G(x)}\exp\left[\int^x \frac{A(x')}{G(x')}dx'\right]. \tag{3}$$

Here, N is the normalization coefficient, $N^{-1} = \int_0^\infty P_{\rm st}(x)dx$. The stationary normalized correlation function of the variable x is written as [12]

$$C(s) = \frac{\langle \delta x(t+s)\delta x(t)\rangle_{\rm st}}{\langle(\delta x)^2\rangle_{\rm st}}, \tag{4}$$

where $\delta x(t) = x(t) - \langle x(t)\rangle$, and $C(s)$ is a measure of the correlation between fluctuations at times t and $t+s$.

Performing the Laplace transformation of the function $C(s)$, we obtain

$$\tilde{C}(w) = \int\limits_0^\infty \exp(-ws)C(s)ds. \tag{5}$$

The associated relaxation time is generally defined by the expression

$$T_C = \int\limits_0^\infty \frac{C(s)}{\langle(\delta x)^2\rangle_{\rm st}}ds. \tag{6}$$

The use of the projection-operation method leads to a continued-fraction expansion for the quantity $\tilde{C}(w)$ [12]. In the zeroth approximation where the memory effects are completely neglected, $C(s)$ relaxes exponentially, $C(s) = \exp(-\gamma_0 s)$, with a relaxation time

$$T_C = \gamma_0^{-1} = \frac{\langle(\delta x)^2\rangle_{\rm st}}{\langle G(x)\rangle_{\rm st}}. \tag{7}$$

By the truncation of the continued-fraction expansion in the first order, the following formula for T_C was obtained [12]:

$$T_C = \left[\gamma_0 + \frac{\eta_1}{\gamma_1}\right]^{-1}. \tag{8}$$

Here,

$$\eta_1 = \frac{\langle G(x)A'(x)\rangle}{\langle(\delta x)^2\rangle_{\rm st}} + \gamma_0^2,$$

$$\gamma_1 = -\frac{\langle G(x)[A'(x)]^2\rangle}{\eta_1\langle(\delta x)^2\rangle_{\rm st}} + \frac{\gamma_0^3}{\eta_1} - 2\gamma_0,$$

where $A'(x)$ is the derivative of A with respect to x.

The first-order approximation for $\tilde{C}(w)$ is determined by the formula [12]

$$\tilde{C} = \frac{w+\gamma_1}{(w+\gamma_0)(w+\gamma_1)+\eta_1}. \tag{9}$$

Performing the inverse Laplace transformation for $\tilde{C}(w)$, it was shown [12] that the correlation function can be written as a sum of two exponentials

$$C(s) = (1-\Delta)\exp(-\Gamma_1 s) + \Delta\exp(-\Gamma_2 s), \tag{10}$$

with

$$\Delta = \frac{\gamma_1 - \Gamma_2}{\Gamma_1 - \Gamma_2},$$

and

$$\Gamma_{1,2} = \frac{1}{2}[\gamma_0 + \gamma_1 \pm \sqrt{(\gamma_1-\gamma_0)^2 - 4\eta}].$$

The parameter Δ defines the importance of the memory effects. If the value Δ is close to unity, then we can use the zeroth order.

3. Stochastic Model for Resonant Tunneling Process

We consider the model of the tunneling system at a resonance described in Ref. [17]. The model considers the open coherent double-barrier tunneling system, where an electron flow described by a wave packet is injected from the left and passes through the tunneling system only once. In Ref. [17], the following differential equation for the complex amplitude D of the wave packet outgoing of the tunneling system was obtained:

$$\frac{D}{dt} = (iz-1)D - i|D|^2 D + D_0, \tag{11}$$

where D_0 is the dimensionless amplitude of the wave function in the incoming flow, $z = L(k-k_r)$ is the parameter proportional to the detuning of the electron wave vector k from the resonance value k_r, L is the inverse half-width of the resonance level in the k-space, which is connected with a half-width in the energy space by the relation $\delta E_{1/2} = 2h\nu = \hbar k_r/(m^*L)$, m^* is the effective electron mass, and $t = \nu t'$ is the dimensionless time.

Going to the intensities $D_0^2 = I_0$, $D^2 = I$, we obtain the following relation between the intensities of the incident I_0 and outgoing I electron flows in the stationary case:

$$I_0 = I[1 + (z-I)^2]. \tag{12}$$

Assuming that the phase of the wave function is not changed in the process of tunneling in a vicinity of the stationary state, the following approximate differential equation can be obtained [19]:

$$\frac{dI}{dt} = -I + \frac{I_0}{1+(z-I)^2}. \tag{13}$$

The system exhibits the bistability as a function of the parameter I_0, if the parameter z satisfies the inequality $z > \sqrt{3}$ [17].

We will consider the intensity of the incident flow I_0 as a stochastic quantity, $I_0 = \langle I_0 \rangle + p(t)$, where $\langle I_0 \rangle$ is the value of incident flow intensity in the absence of noise, and $p(t)$ are fluctuations of the intensity described by a Gaussian noise with zero mean and the correlation function $\langle p^*(t)p(t) \rangle = \frac{D}{\tau_1} \exp\left(-\frac{|t-t'|}{\tau_1}\right)$, where D is the noise strength, and τ_1 is its self-correlation time.

We suppose that there are also fluctuations of the detuning parameter $z = \langle z \rangle + q(t)$, where $q(t)$ is a noise term with zero mean and the correlation function $\langle q^*(t)q(t) \rangle = \frac{Q}{\tau_2} \exp\left(-\frac{|t-t'|}{\tau_2}\right)$, with Q being the noise intensity, and τ_2 the time of its self-correlation.

Then we come to the Langevin equation

$$\frac{dI}{dt} = -I + \frac{I_0}{1 + (z - I)^2} + g_1(I)p(t) + g_2(I)q(t) \quad (14)$$

with $g_1 = \frac{1}{1+(z-I)^2}$, $g_2 = \frac{2I(I-z)}{1+(z-I)^2}$ obtained by expanding the nonlinear terms to the first order in I.

In order to consider the self-correlation times of noises and their mutual cross-correlation time, we have to go to the Fokker–Planck equation given by expression (2). In the numerical calculations of the intensity correlation functions $C(s)$ and the associated relaxation times T_C, we use expressions (10) and (8), respectively.

4. Calculation of the Intensity Correlation Functions and Relaxation Times

We now analyze the behavior of the relaxation time T_C as a function of the parameters of the process and noises. The relaxation time gives the information about the time scale of the fluctuation evolution.

In Fig. 1, the dependence of the relaxation time T_C on the mean value of the incoming intensity I_0 for various values of noise strength D is represented.

It can be seen that, for the small noise strength ($D = 0.1$), the maximum of T_C (that implies the slowing down of the process) takes place close to the point of the transition from the state with low tunneling effectiveness to the state with high effectiveness ($I_0 = 5.2$). As the noise strength D increases, the maximum shifts to larger values of I_0, thereby increasing the stability of the system.

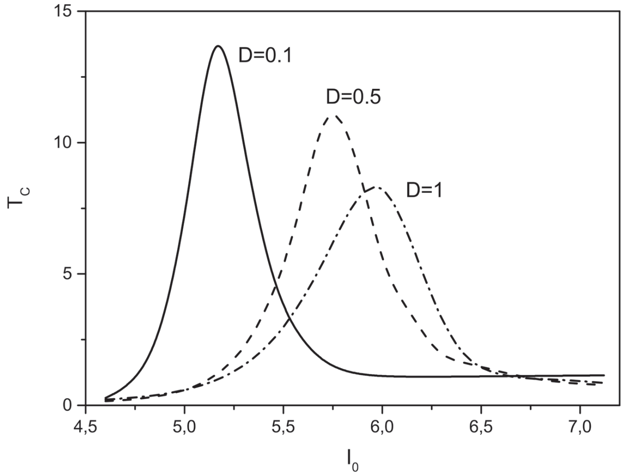

Fig. 1. Relaxation time T_C as a function of the mean value of the incident flow intensity I_0 for the various values of noise strength D and the parameters $\lambda = 0.1$, $Q = 0.1$, $\tau_1 = \tau_2 = \tau_0 = 0.1$

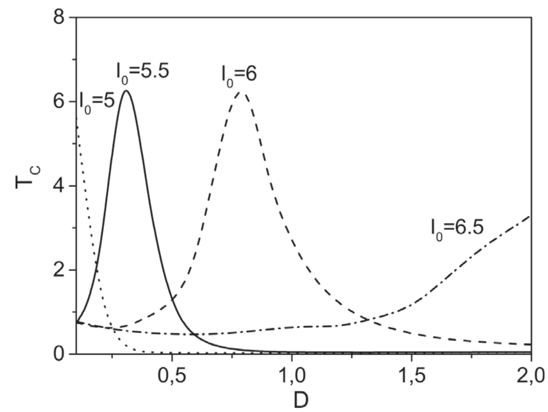

Fig. 2. Dependence of the relaxation time T_C on the noise strength D for the various values of incident flow intensity I_0 with the parameters $\lambda = 0.8$, $Q = 0.1$, $\tau_1 = \tau_2 = \tau_0 = 0.1$

In Fig. 2, the relaxation time T_C as a function of the noise strength D is plotted for various mean intensities. We see that if the noise is absent ($D = 0$), T_C has a maximum close to the deterministic transition point (which occurs at $I_0 = 5.0$ for this set of parameters). Increasing D results in a shift of the transition point to larger values of I_0 similar to Fig. 1. In this region, T_C as a function of D grows with D, passes through the maximum, and decreases for larger

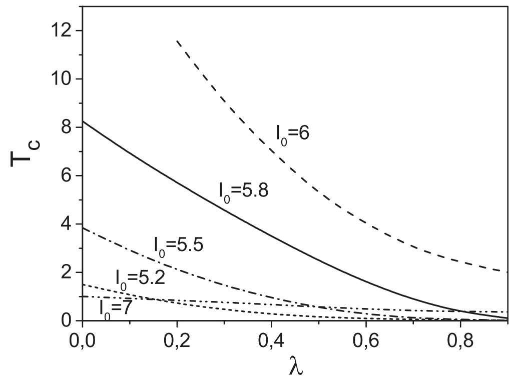

Fig. 3. Relaxation time T_C as a function of the cross-correlation strength λ for the various values of mean incident flow intensity I_0 with the parameters $D = 1$, $Q = 0.1$, $\tau_1 = \tau_2 = \tau_0 = 0.1$

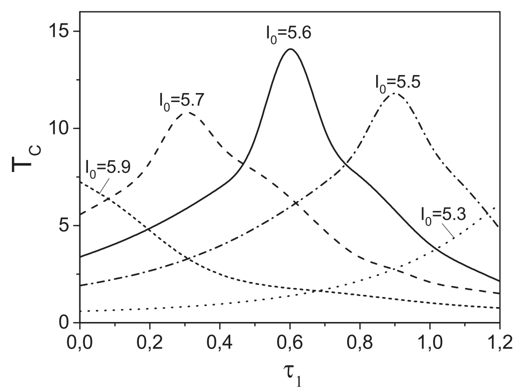

Fig. 4. Dependence of T_C on the self-correlation time τ_1 of $p(t)$ noise for the various values of mean incident flow intensity I_0 with the parameters $\lambda = 0.5$, $D = 0.5$, $Q = 0.1$, $\tau_2 = \tau_0 = 0.1$

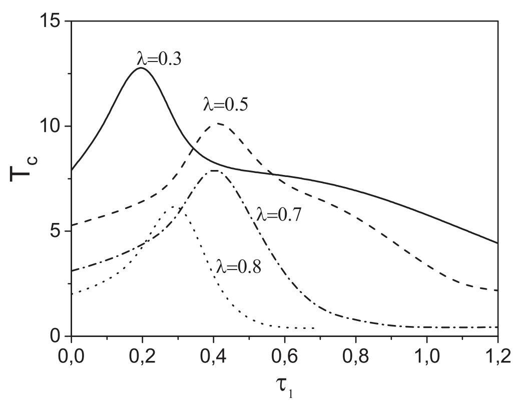

Fig. 5. Dependence of T_C on the self-correlation time τ_1 of $p(t)$ noise close to the transition point (I_0=5.7) for the various cross-correlation strengths λ and with the parameters $D = 1$, $Q = 0.1$, $\tau_1 = \tau_2 = \tau_0 = 0.1$

D. Such a behavior is the evidence of a stochastic resonance phenomenon.

The relaxation time T_C as a function of the correlation strength λ between two noises is depicted in Fig. 3 for various values of the mean incident flow intensity I_0.

It can be seen that T_C monotonically decreases, as λ increases. For a fixed value of λ, T_C has the largest value near the threshold ($I_0 = 6$) and the smallest values in the regions below ($I_0 = 5.2$) and above the threshold ($I_0 = 7$).

Now, we analyze how the memory effects influence the relaxation time. T_C as a function of the self-correlation time τ_1 of the intensity fluctuations $p(t)$ for various values of the mean incident flow intensity I_0 is shown in Fig. 4. For the parameters used, the transition from the low to high state occurred near the point $I_0 = 5.6$.

It follows from Fig. 4 that the dependence of T_C on τ_1 has the most pronounced character with the maximum at the definite value of τ_1 only in a vicinity of the transition point. As τ_1 increases, the maximum of T_C can be observed at smaller values of the incident intensity. Therefore, we can conclude that the transition is facilitated with the growth of the correlation time of noise $p(t)$.

In Fig. 5, we can see how this dependence for $I_0 = 5.7$ is changed with the cross-correlation strength λ.

It can be noted that the maximum of T_C shifts with respect to the cross-correlation strength λ in a different way. For the moderate values of cross-correlation intensities λ ($\lambda = 0.5$–0.7), the maximum takes place at the larger values of τ_1 than for small ones ($\lambda = 0.3$), as well as for large ($\lambda = 0.8$) ones.

In Fig. 6, we plot the function T_C vs I_0 for the various values of self-correlation times τ_1 and τ_2 of noises $p(t)$ and $q(t)$, respectively, and of their cross-correlation time τ_0. It can be observed that an increase in the correlation times of noises leads to a shift of the maximum of the relaxation time T_C. When the correlation times of noises have minimum values ($\tau_1 = \tau_2 = \tau_0 = 0.01$), the maximum of T_C is situated at $I_0 = 5.8$ (see the solid curve). The growth of the correlation time τ_1 of fluctuations of the intensity to the value $\tau_1 = 0.5$ results in the shift of the maximum to the left to the value of $I_0 = 5.6$. The increase of τ_2 (self-correlation time of frequency fluctuations) to 0.5 causes the shift of the maximum to the right to the value of $I_0 = 6.1$. On the other hand, the growth

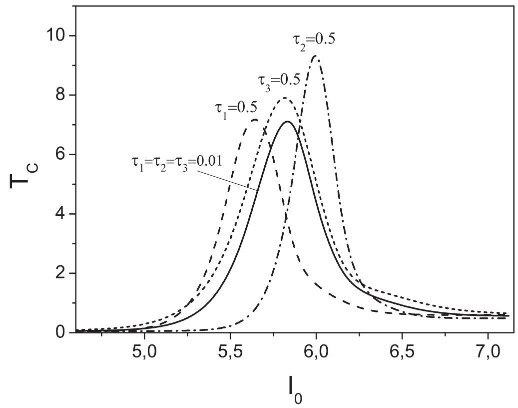

Fig. 6. Relaxation time T_C as a function of the mean incident intensity for the various correlation times of noises with the parameters $\lambda = 0.5$, $D = 0.5$, $Q = 0.1$

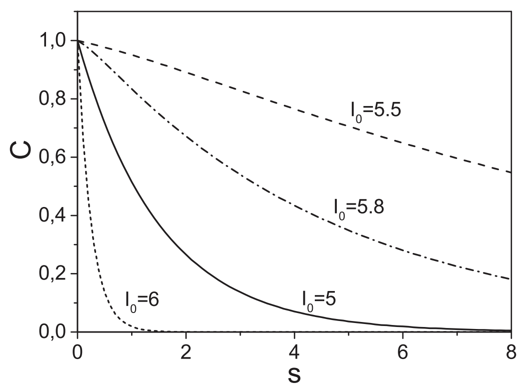

Fig. 7. Correlation functions $C(s)$ for the various mean values of incident intensity I_0 when parameters values were $\lambda = 0.1$, $D = 0.5$, $Q = 0.1$, $\tau_1 = \tau_2 = \tau_0 = 0.1$

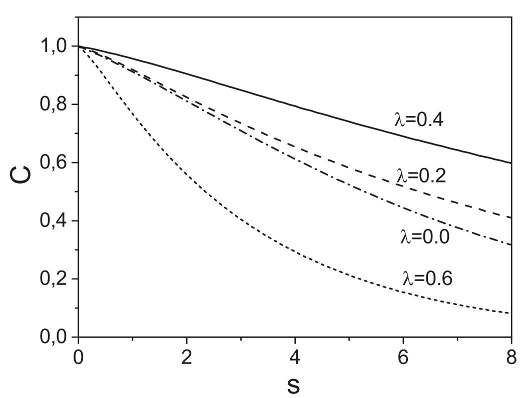

Fig. 8. Correlation function $C(s)$ in the vicinity of the transition point ($I_0 = 5.8$) for the various values of cross-correlation strength λ with the parameters $D = 0.5$, $Q = 0.1$, $\tau_1 = \tau_2 = \tau_0 = 0.1$

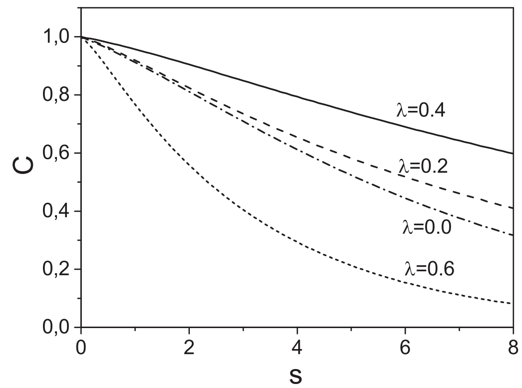

Fig. 9. Correlation function $C(s)$ in a vicinity of the transition point ($I_0 = 5.8$) for the various noises strengths Q of the noise $q(t)$ with the parameters $D = 0.5$, $\lambda = 0.5$, $\tau_1 = \tau_2 = \tau_0 = 0.1$

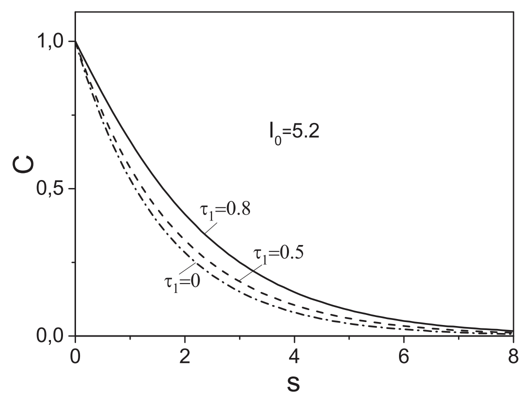

Fig. 10. Correlation functions for the various values of noise $p(t)$ correlations times τ_1 for the process being before the threshold) with the parameters $D = 0.5$, $Q = 0.1$, $\lambda = 0.5$, $\tau_2 = \tau_0 = 0.01$

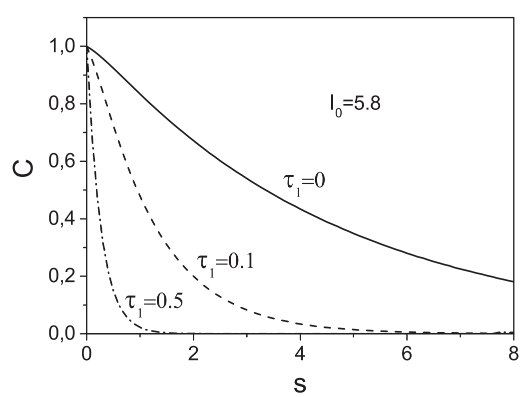

Fig. 11. Correlation functions for the various values of noise $p(t)$ correlations times τ_1 for the process being after the threshold with the parameters $D = 0.5$, $Q = 0.1$, $\lambda = 0.5$, $\tau_2 = \tau_0 = 0.01$

of the mutual correlation time τ_0 to the value of 0.5 does not result in a shift of the curve.

The behavior of the normalized intensity correlation function $C(s)$ for the various parameters of the process and noises is represented in Figs. 7–12. In Fig. 7, the correlation functions of the process are plotted in the cases where the value of mean incident intensity for the given parameters was below the transition point ($I_0 = 5$) in its vicinity ($I_0 = 5.5$) and above it ($I_0 = 5.8, 6.0$).

It can be seen in Fig. 7 that $C(s)$ decays most rapidly above the transition ($I_0 = 6$) and below it ($I_0 = 5$). But, close to the transition ($I_0 = 5 \div 5.8$), its decay slows. Such a behavior indicates that the fluctuations increase as the process approaches the instability point resulting in an increase of the area under the $C(s)$ curve, which defines the relaxation time.

In Fig. 8, the dependence of $C(s)$ on the degree of the correlation between the noises λ is shown. We found that the $C(s)$ decay is slowing, as λ increases from the value 0.2 to 0.4 (the area under the curve increases), and then accelerates for larger values of λ (the area under the curve contracts). Thus, the correlation strength λ between two noises can accelerate the fluctuation decay.

Let us see how the intensity Q of the frequency noise $q(t)$ affects the behavior of the intensity correlation function $C(s)$. This is demonstrated in Fig. 9, where it can be observed that the smallest decay of the correlation function (an increase of fluctuations is a characteristic of the transition) takes place at the definite value of the noise intensity Q. This means the existence of a stochastic resonance phenomena for this noise similar to the $p(t)$ noise.

The influence of the self-correlation times of noises and their mutual cross-correlation time on the behavior of the intensity correlation function depends strongly on the acting point of the process with respect to the point of transition. It is illustrated in Figs. 10–11, where the correlation functions for the various values of $p(t)$ noise correlation times τ_1 are depicted for the process being below the threshold (Fig. 10) and above it (Fig. 11).

Below the threshold, we can see that the rate of correlation function decay becomes slower, as the noise correlation time τ_1 increases. On the contrary, above the threshold (Fig. 11), the correlation function decay increases with τ_1. Therefore, in the pre-threshold region, the growth of the noise correlation time increases fluctuations; while, in the after-threshold region, it results in their decrease.

We have found that the dependences of the correlation function on the self-correlation time τ_2 of the frequency noise and the cross-correlation time τ_0 have a similar character.

5. Conclusion

By means of numerical calculations, we have analyzed the influence of colored cross-correlated noises on the outgoing flow intensity correlation function $C(s)$ and the associated relaxation time T_C within a model of resonant tunneling. It has been found that that the stability of the system increases with the strength D of noise that models fluctuations of the incident flow intensity I_0. There exists the dependence of the relaxation time on the intensity of the noises that is typical of the stochastic resonance phenomenon. We have shown that T_C monotonically decreases, as the correlation strength λ between two noises increases. It has been shown also that the cross-correlation strength λ can facilitate the fluctuation decay. We have obtained that the growth of the self-correlation time τ_1 of the intensity fluctuation noise τ_1 results in a shift of the threshold of the transition to the high state to lower values of the incident intensity I_0 with respect to the deterministic case, while the increase of the correlation time τ_2 of frequency fluctuations shifts the threshold to the larger values of I_0. Thus, the time τ_1 growth accelerates the transition; on the other hand, the stability of the system increases, when τ_2 grows.

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О.О. Понежа

ЧАСИ РЕЛАКСАЦІЇ ТА КОРЕЛЯЦІЙНІ ФУНКЦІЇ ПІД ВПЛИВОМ КРОС-КОРЕЛЬОВАНИХ ШУМІВ У МОДЕЛІ РЕЗОНАНСНОГО ТУНЕЛЮВАННЯ

Р е з ю м е

Розглянуто вплив крос-корельованих шумів на процес релаксації флуктуацій у моделі резонансного тунелювання, в якій передбачалась наявність джерел шумів, пов'язаних з флуктуаціями інтенсивності та частоти в падаючому потоці. Для характеристики динамічної поведінки системи розраховувалися нормовані функції кореляції і асоційовані часи релаксації за допомогою методу проекційного оператора з урахуванням ефектів пам'яті. Проаналізовано вплив на ці функції інтенсивностей шумів, їх часів кореляції, а також сили взаємної кореляції і часу крос-кореляції. Було знайдено, що сила кореляції між двома шумами може прискорити розпад флуктуацій інтенсивності. Залежність часу релаксації від інтенсивності шумів може бути охарактеризована як стохастичний резонанс. Було показано, що збільшення часу кореляції флуктуацій інтенсивності прискорює перехід з нестабільного стану, у той час як ріст часу кореляції флуктуацій частоти затримує перехід, тим самим збільшуючи стабільність системи.