NOISE CHARACTERISTICS AND INSTABILITIES OF LONG JOSEPHSON JUNCTIONS†

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Abstract

In a magnetic field, current biased long Josephson junctions exhibit the dynamics of fluxon motion which are affected by fluctuations. These consist of telegraph noise at voltage steps and instabilities due to chaotic behavior. Results on long junctions with McCumber number β_c ranging from 10 to 100 show such behavior. The telegraph noise is driven by thermal fluctuations. Modeling of our junctions using a perturbed sine-Gordon equation shows the chaotic regions and the periodic ones.

Introduction

The motion of fluxons in long Josephson junctions can be used in a variety of analog and digital circuits[1,2]. Since these circuits rely on the control of fluxon motion, it is important to know the effects of noise and instabilities. Of special interest to circuit design and applications is the chaotic behavior of junctions and how such behavior is approached. The quantum phase ϕ in a long Josephson junction, of length L greater than the Josephson penetration depth λ_J, obeys a perturbed sine-Gordon equation of the form

$$\phi_{tt} - \phi_{xx} + \left(\beta_c^{-1/2}\right) \phi_t + \sin \phi = J \qquad (1)$$

Here distances are in units of the Josephson penetration depth λ_J and time in units of $1/\omega_J$, the reciprocal of the Josephson plasma frequency ω_J. The right hand side of this equation contains the external drive terms, in our case a d.c. current density J normalized to the critical Josephson supercurrent density J_c, and β_c is the dimensionless McCumber hysterisis parameter equal to $(2eI_cR^2C/\hbar)$. Here, R is the junction resistance, C its capacitance and I_c its critical Josephson supercurrent. Large β_c means small damping. A d.c. bias by itself can produce fluxon oscillations inside the junction which lead to zero field steps in the I-V curve of the junction. In the presence of a magnetic field the symmetry of fluxon motion is modified leading to propagating fluxons and electromagnetic waves in the cavity of the junction; this is evidenced by the Fiske steps in the I-V curve of the junction. The voltage step structure corresponds to phase-locked solutions where noise and instabilities can lead to all sorts of fluctuations. We will describe our study of such fluctuations and instabilities.

Experimental Details

Long Josephson junctions were fabricated with Niobium electrodes and Aluminum Oxide barrier; they were 130 μm long and 6μm wide with current densities ranging from 100 A/cm^2 to 3 x 10^3 A/cm^2. For such junctions studied here β_c was in the range of 10 to 100. To obtain a uniform current density, eight injection fingers were used in an overlap type of geometry. A 70 μm wide control line was placed above the junction to couple in magnetic field. The junctions were cooled to 4.2K in a probe with electrostatic and magnetic shielding, the earth's field being compensated to a few milligauss. All the leads going to the sample were filtered and shielded.

In the presence of a magnetic field due to the control current, a current step structure was induced in the I-V curves. The junction was biased using the gate current I and the control current I_s; fluctuations were then studied at various parts of the I-V curve, in the voltage state.

Results

A. Telegraph Noise

The dynamics of fluxons in a biased long junction in a magnetic field lead to a step structure in the I-V curve corresponding to the various modes of motion. The voltage steps are spaced by a voltage of $\frac{\phi_o \bar{c}}{2\,L}$ where $\bar{c}$ is the fluxon terminal speed, L the length of the junction, and ϕ_o the flux quantum. Such a step structure, each with its own energy, corresponds to traps with a fixed number of fluxons at a given step. When biased at a voltage step which is a metastable state, the junction switches to the next step as a result of fluctuations. This leads to telegraph noise as the junction switches back and forth between the 2 states. Such telegraph noise has been observed in a variety of systems, ranging from semiconductors to high T_c materials[3-6]. A typical voltage-time behavior for our junctions is shown in Figure 1.

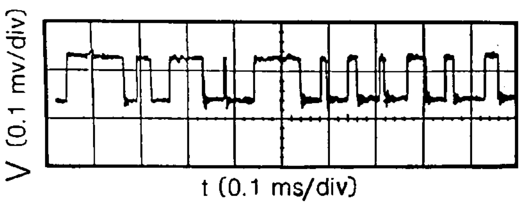

Figure 1 - A typical measured telegraph noise.

The magnitude of the voltage is 50 μ volts corresponding to the voltage difference between 2 adjacent current steps. The power spectrum of this noise corresponds to a Lorentzian distribution in the form

$$W(\omega) = \frac{A\tau_o}{(1+\omega^2\tau_o^2)} \qquad (2)$$

which is characteristic of a 2-level system, having lifetimes τ_1 and τ_2 in each level; here $\tau_o^{-1} = \tau_1^{-1} + \tau_2^{-1}$. Our results show that the mean lifetime τ_o increases with the current width ΔI

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which is the width over which a given step is bistable. Within the current uncertainty $\Delta I = I_n - I$ the long junction can switch from the n- state fluxon current step to one at n+1.

In order to understand the origin of this noise, we have investigated the temperature dependence of the current width ΔI. This is the classical problem of a particle, the fluxon here, with thermal energy kT trying to escape over a barrier ΔU which is larger than kT. It has been shown[7,8] that within such a model the current width has a temperature dependence given by ΔI being proportional to $T^{2/3}$, while the lifetime for a fluxon remaining in the lower state being described at high temperatures by:

$$\frac{1}{\tau} = \frac{\omega_1^2}{2\pi\eta} e^{-\frac{\Delta U}{kT}} \qquad (3)$$

where ω_1 is the fluxon attempt rate in going over the barrier and η is a damping parameter = 1/RC. Our results show indeed that we have such temperature dependence and that we are in the thermal activation regime.

B. Chaotic Behavior

Chaotic states in small Josephson junctions driven by rf - and dc - current have been studied extensively[9]. For a long Josephson junction, the perturbed sine-Gordon equation with ac - driving force also gives rise to chaos[10]. However, the chaotic behavior of a long Josephson junction in a constant external magnetic field without an external ac driving term has not been fully studied yet. Intermittent chaos between Fiske steps[11] is the only result reported so far.

In the following, some results on this subject will be presented. Since our junctions follow the highly non-linear equation 1 with dissipation, for some parameters of the junction, chaotic behavior is expected. This comes from experimental observation of regions of the I-V curves having much more high frequency noise than other regions. A typical I-V curve having large amounts of noise in some regions is shown in Figure 2.

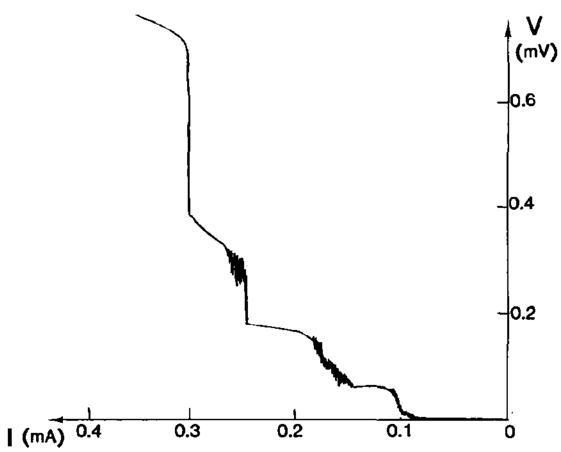

Figure 2 - The experimental I-V curve for a long Josephson junction with I_c = 1.2mA, L = $3\lambda_J$. The control current I_s was 1.5mA.

In this particular situation large noise was observed between the first and third step (the second step is almost missing) and at the beginning part of the last step. The power spectrum of this noise is white within the limit of our instrumentation (<1 MHz). Such high frequency noise is observed quite often in certain parts of the I-V curve. Figure 3 is another case which shows that large amounts of white noise occurs in a region between the zero and first step.

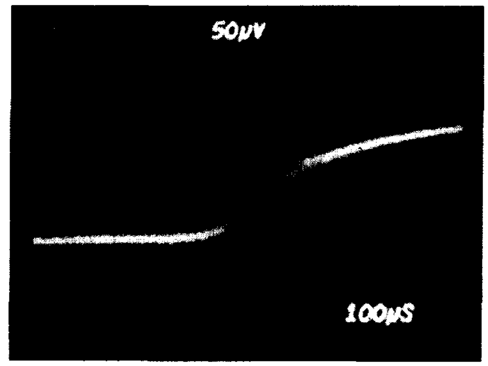

Figure 3 - Part of I-V curve for a long Josephson junction with I_c = 23mA, L = $13\lambda_J$. The control current I_s was 27mA.

In order to verify that such noise was really caused by chaos, computer simulations were done on a Vax 11/785-VMS machine for junctions behaving according to equation 1. A finite difference method[12] has been used for the calculations. The one fluxon initial condition was used at the beginning. As soon as the system was on the Fiske step, the previous result was used as the initial condition. The J-$\bar{\phi}_t$ curve obtained with β_c = 14.8, L = $5\lambda_J$, in an external field of H = 1.25 $J_c\lambda_J$, is depicted in Figure 3. $\bar{\phi}_t$ was calculated at the left end of the junction. Figure 3 shows that three Fiske steps are obtained from the computer simulation. Between these steps chaotic behavior which is characterized by intermittent jumping between two adjacent coherent states is observed. This is consistent with the result obtained by Soerensen et al.[11]. An important result presented here is that even within Fiske steps chaotic motion can occur. Figure 4 shows that, near the ends of first and second Fiske steps, the system is in the chaotic states.

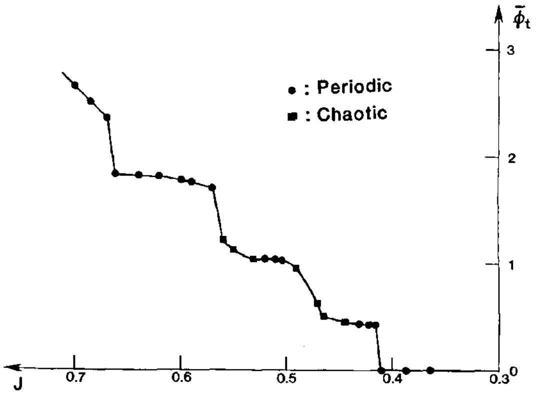

Figure 4 - The computer simulation result of current - voltage characteristics for $L = 5$, $\beta_c = 14.8$, $H = 1.25\ J_c\lambda_J$.

Figure 5a depicts the power spectrum for the periodic solutions obtained at $J = 0.42$; while Figure 5b, which was obtained at $J = 0.44$, shows the chaotic behavior characterized by a broadband noise.

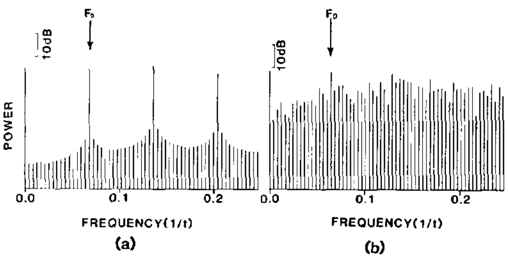

Figure 5 - Computer simulation results of power spectra of ϕ_t. F_o is the Josephson frequency. (a) $J = 0.42$, (b) $J = 0.44$. Other parameters are the same as those in Figure 4.

These two points both belong in the first Fiske step. The experimental results illustrated in Figure 2 and Figure 3 are qualitatively reproduced by the computer simulations, which indicate that the white noise with large amplitude observed in the experiment has indeed originated from chaotic motion.

Conclusion

Noise characteristics and chaotic behavior of long Josephson junctions in the magnetic field are investigated. In the experiments, telegraph noise is observed when the junction is biased at metastable states, switching back and forth between adjacent steps as a result of thermal fluctuations.

Chaotic behavior is found both experimentally and numerically. In the experiments, chaotic regions which are characterized by white noise with large amplitude are found. Some of the chaotic regions are between Fiske steps, while others are at the edge of the Fiske steps. These observations are confirmed by our numerical calculations.

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