SOFT AND HARD TURBULENCE

IN LONG RF-BIASED JOSEPHSON JUNCTIONS

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1. INTRODUCTION

This chapter is concerned with the turbulent behavior, an interesting and fundamental dynamical state not well understood. Once it had been established that *chaos is not turbulence*, the turbulent phenomenon has received a great deal of attention in recent years[1-6].

Systems with many degrees of freedom can develop coherent structures (spatiotemporal patterns). In this way the system reduces the effective number of degrees of freedom and is able to exhibit periodic and low-dimensional chaotic *(in time)* behavior. The activation of new degrees of freedom can give rise to turbulent-like dynamics (incoherent in space and *disordered in space as well as in time*).

In Fig.1 we present the contrast between these different dynamics: Fig. 1(a) shows a typical low-dimensional Poincaré map for a chaotic dynamic, whereas Fig. 1(b) corresponds to fully developed spatiotemporal, turbulence in which the attractor completely loses fractality and autosimilarity (intimately related with the underlying mechanism of the chaotic phenomena). The low-dimensional strange attractor is destroyed due an activation of an increased number of effective degrees of freedom. Actually the notion that an attractor underlies turbulent behavior is under suspect: according to Crutchfield and Kaneko[2], long transients preclude observation of the behavior ruled by the asymptotic invariant measure and the nature of the attractor is irrelevant to the observed behavior.

In 1987, Heslot, Càstaing and Libchaber[1] reported a Rayleigh-Bénard experiment which followed the transition fron chaos to soft and hard turbulence. The soft turbulence regime can be regarded as a dynamical state globally disordered in space and in time. This state contrasts with the hard turbulence

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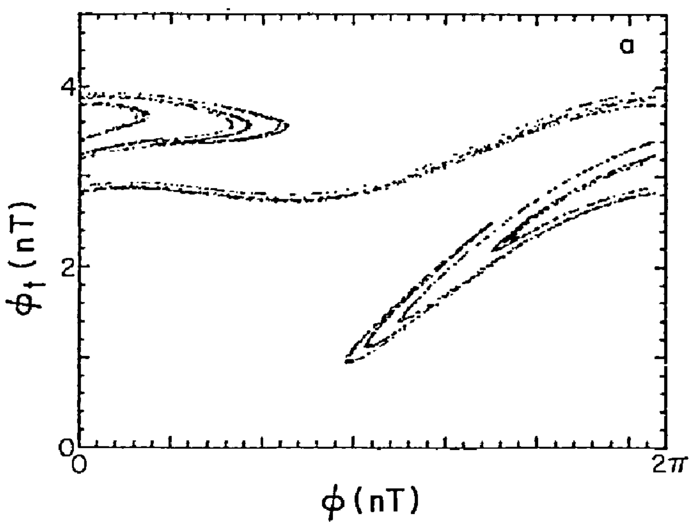


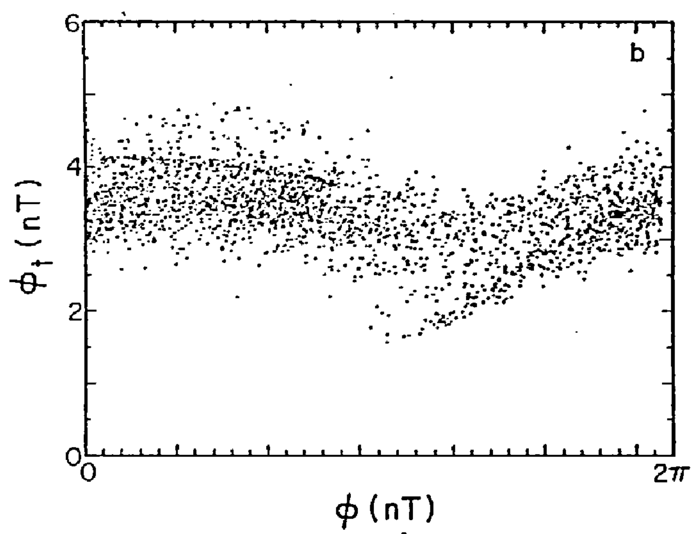


Fig. 1. From chaos to disorder. (a) Poincaré map showing a typical strange attractor for low-dimensional chaos. (b) The strange attractor is destroyed as spatial correlation decays.

regime in which the pattern formation and conversion induces a reemergence of coherence in a narrow frequency range.

The solitonlike character of the the long Josephson junction can play a fundamental role as an activating mechanism of chaos and introduces a rich variety of new and interesting spatiotemporal phenomena[7,8]. Even richer behavior can also be exhibited by the the long Josephson junction, like regimes of soft and hard turbulence[6]. The aim of this chapter is to present the study of turbulent regimes in long Josephson junctions as a field which provides an insight of what determines the ability of a system to become turbulent.

This chapter is organized as follows: in Sec. 2 we present a description of the forced long Josephson junction. In Sec. 3 we explore the transition to the soft turbulent state. In Sec. 4 we contrast the soft and the hard turbulence regimes. Finally, in Sec. 5 we summarize and present our conclusions.

2. THE LONG JOSEPHSON JUNCTION

The forced long Josephson junction considered by us has been discussed extensively[9]. We model this system with the usual sine-Gordon-like equation,

$$\phi_{xx}-\phi_{tt}-\sin\phi=\alpha\phi_t-\rho\sin(\Omega_d t) \tag{1}$$

where $\phi=\phi(x,t)$ is the phase difference of the superconducting order parameter between each side of the barrier and its derivative in time is the voltage across the junction. The term $\alpha\phi_t$ represents quasiparticle loss. The distance is normalized to the Josephson penetration depth λ_J , time is normalized to the inverse of the Josephson plasma frequency, the rf amplitude ρ is normalized to the critical current and Ω_d is the normalized applied frequency. The external applied field is taken into account through,

$$\phi_x(0,t)=\phi_x(L,t)=\eta \tag{2}$$

where L is the junction length and η is a measure of the external magnetic field.

The perturbed sine-Gordon equation is the simplest wave-equation for a periodic medium and occurs frequently in solid-state physics. The system described by eqs.(1,2) is in fact analogous to a chain of coupled pendula forced by an external torque. This analogy indicates that the turbulent behavior can be present not only in fluids but also in solid-state and mechanical systems described by relatively simple models.

3. ONSET OF SOFT TURBULENCE

The study of the route to turbulent-like behavior can establish what determines the ability of the system to become turbulent, providing in this fashion a better understanding of the turbulent state.

In this section we explore the onset of soft turbulence in long Josephson junction as the amplitude of a radio-frequency (rf) drive is increased. Parameter values are $L = 10\lambda_J$, $\alpha = 0.252$ and $\Omega_d = 0.65$. We employ open boundary conditions, $\eta = 0.0$, spatially uniform drive and flat initial conditions. Thus the pattern formation phenomena is fully spontaneous in contrast with Rayleigh-Bénard experiments in which symmetry breaking and consequent pattern formation is induced via boundary conditions. In addition, our results were obtained in the absence of thermal noise.

3.1. Spontaneous Pattern Formation and Symmetry Breaking

In most physical situations the development of turbulence is preceded by the formation of spatiotemporal structures. Hereafter we show that in the case of the long Josephson junction the pattern formation phenomenon can be autonomously excited.

For a long Josephson junction with $\rho = 2$ we find a transition from a transient with period 1 to a period 2 regime. This transition at first sight might appear to be a simple bifurcation in time as in low-dimensional systems. However, as shown in Fig. 2(a) (where we plot the phase difference $\Delta\phi$ between two points of the junction for each period of the rf drive as a function of time) the voltage is no longer homogeneous in space. The fact that $\Delta\phi$ repeats only every second period shows that the spatial extent of the junction has now become significant. Figure 2(b) reveals the spatiotemporal profile sustained by the system after the homogeneous transient: a "virtual" breather (a solitonlike state with an internal degree of freedom) centered at the edge of the junction is formed with only half of it present inside the junction. This "virtual" breather switches at each period between its two states, thus yielding a steady state in which the spatial symmetry is broken, much like the symmetry-breaking precursor (in phase space) of the usual transition to chaos. Fig. 2(b) can be interpreted to be the inability of the system to sustain a soliton commensurate with its size, jumping instead into a sort of bifurcation in space. The system thus succeeds in breaking the symmetry in real space and not in phase space as in temporal chaos.

3.2 The Two-Frequency Route to Turbulence

Below we present the development of turbulence as concerning the involvement of new degrees of freedom via the breakdown of coherence of the spatiotemporal profile.

As ρ is increased, once the breather forms from the initial flat condition there is long transient both in space and in time: there is an increasing difficulty of the system to attain a response which oscillates locked to the frequency of the driving force. The inner bands in Fig. 3 corresponds to a regime ($\rho = 2.0079$) that after such a long transient finally reaches the state with a breather oscillating with a frequency equal to half the driver (Fig. 2(b)).

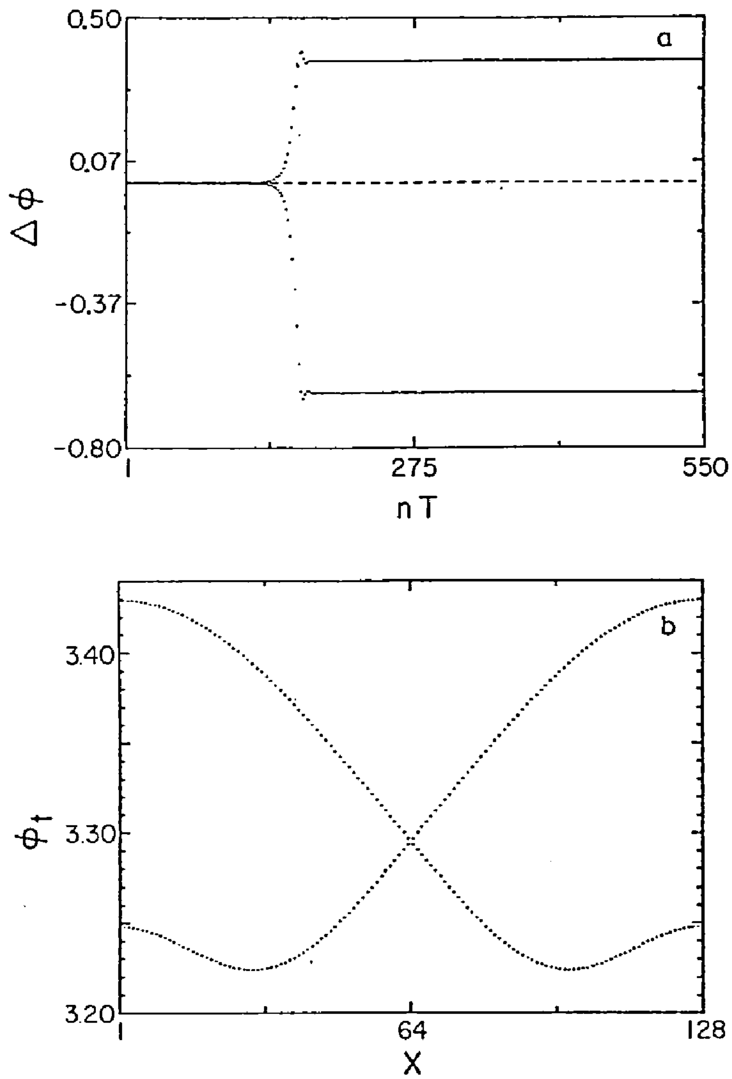


Fig. 2. *Spontaneous Symmetry Breaking.* (a) The difference of the phase between two points of the junction $\Delta\phi$ *vs* nT (T is the period of the harmonic drive). For n > 180, $\Delta\phi$ oscillates between the upper and lower curves revealing the development of a spatiotemporal profile. (b) Strobed profile $\phi_t(x, nT)$ *vs* x showing nonsymmetric breather oscillation.

As the system is driven harder the system ceases the long transient behavior in space and in time via generation of a quasiperiodic response. This quasiperiodic regime is possible because the spatiotemporal excitation oscillates at a frequency inconmensurate with the external drive. The outer bands in Fig. 3 presents for $\rho = 2.01$ the generation at the very onset of pattern formation of a breather-like excitation unlocked to the frequency of the driving force.

The coherence of the spatial profile decreases as the forcing is increased further as we present in Fig. 4(a). Thus the final state is disordered not only in time but in space and can be regarded as a soft-turbulent like regime, a regime in which there is a breakdown of the pattern formation ability of the system[1,6].

The underlying mechanism of the transition to the soft turbulent regime is the following[10]: in the quasiperiodic regime, different points of the junction differ in the way the different frequencies linearly combine. This has the effect of reducing the coherence of the spatiotemporal profile which decreases as the forcing is increased further.

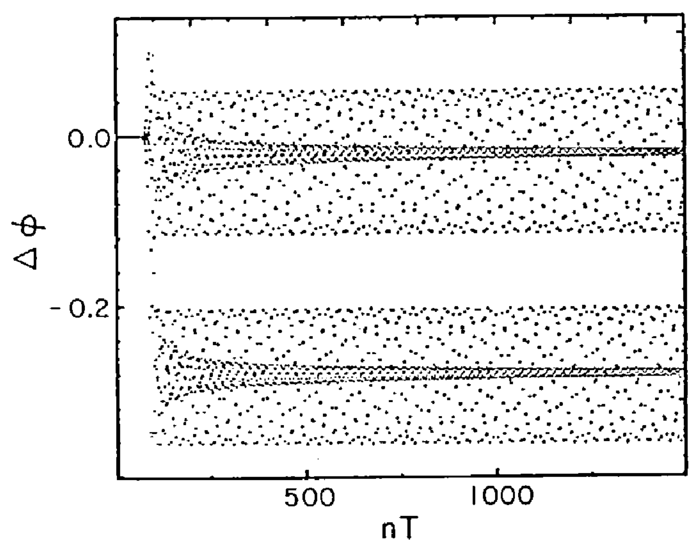


Fig. 3. Difference of the phase between two points of the junction $\Delta\phi(nT)\, vs\, nT$ for a regime with a long transient in space and time at $\rho = 2.0079$ (inner bands) and a quasiperiodic regime at $\rho = 2.01$ (outer bands).

4. SOFT AND HARD TURBULENCE

An applied magnetic field can excite pattern formation and destruction phenomena in the long Josephson junction. This system exhibits a hard turbulence regime when parameter values are $L = 5\lambda_J$, $\alpha = 0.252$, $\Omega_d = 0.65$, $\rho > 0.7375$ and $\eta = 1.25$. With these constraints the dynamical behavior corresponds to the regime of creation and destruction of fluxons[8].

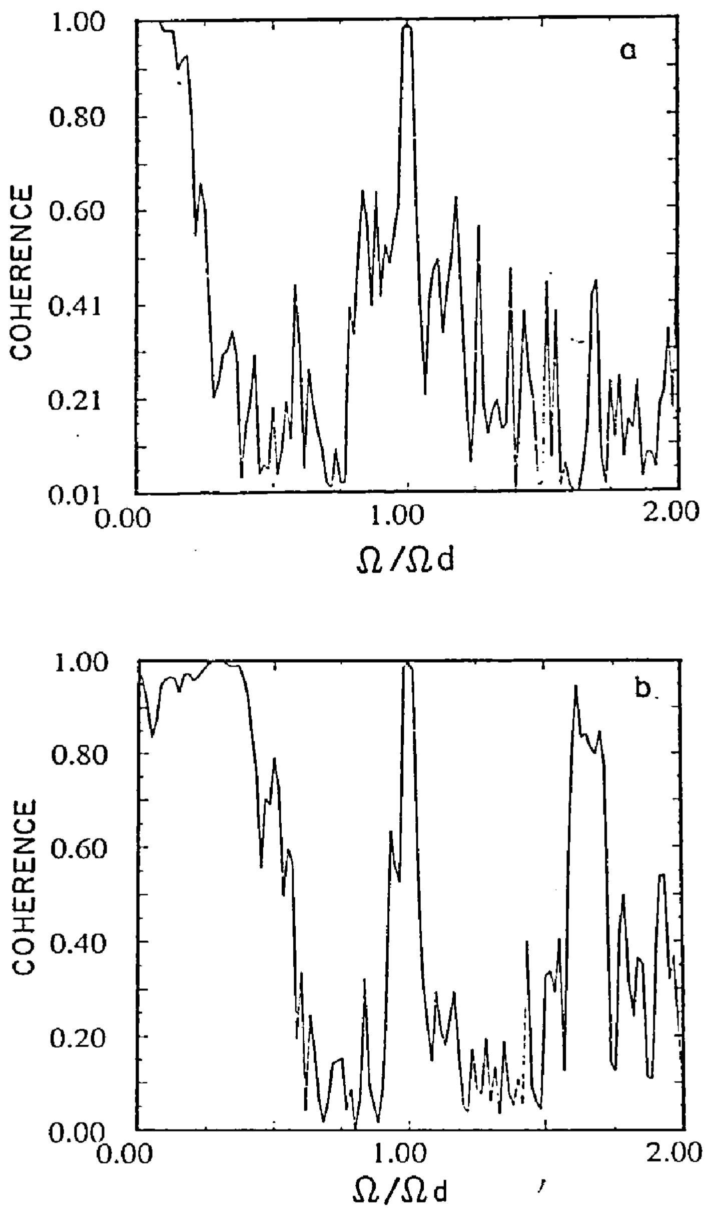


Fig. 4. Coherence spectra. (a) Soft turbulence: spatial coherence dissapears for all values but those of very low frequencies and the driving frequency. (b) Hard turbulence: spatial coherence dissapears for all but one frequency (other than the driving frequency).

In Fig. 4(b) we present the coherence spectrum for this fluxonic regime: coherence dissapears for all but one frequency (other than the drive frequency). This is in contrast with the soft turbulent regime (Fig. 4(a)) in which spatial coherence dissapears completely.

The statistics of the voltage recordings are very different in the two types of turbulent behaviors as is shown by the histograms of fluctuations in both regimes (Fig.5(a,b)). However, these histograms are also different from those reported for the Rayleigh-Bénard system[11] suggesting that this characterization might not provide a universal clear-cut distinction between the two regimes.

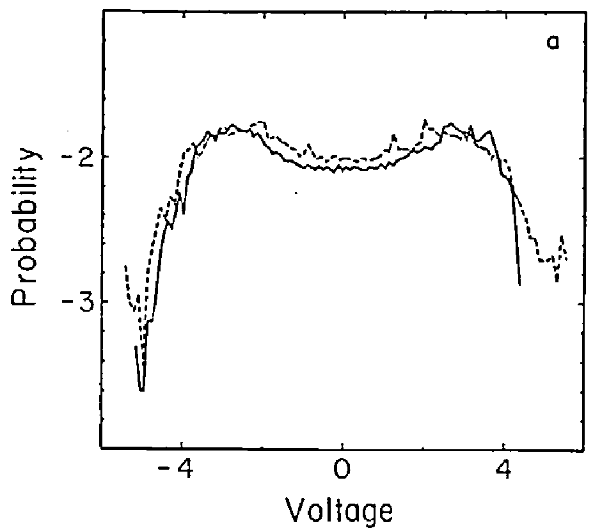


Fig. 5(a). Histogram of voltage fluctuations for soft turbulence. The continuous line represents the fluctuations for the signal at $x = L/2$ whereas the dashed lines corresponds to the signal at $x = L'$.

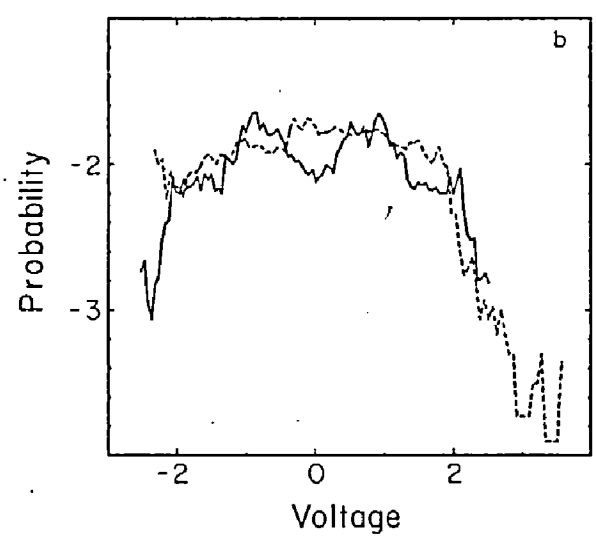
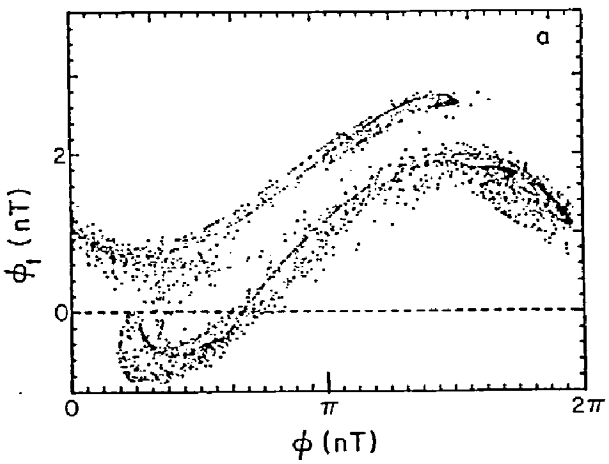


Fig. 5(b). Histogram of voltage fluctuations for hard turbulence. The continuous line represents the fluctuations for the signal at $x = L/2$ whereas the dashed lines corresponds to the signal at $x = L'$.



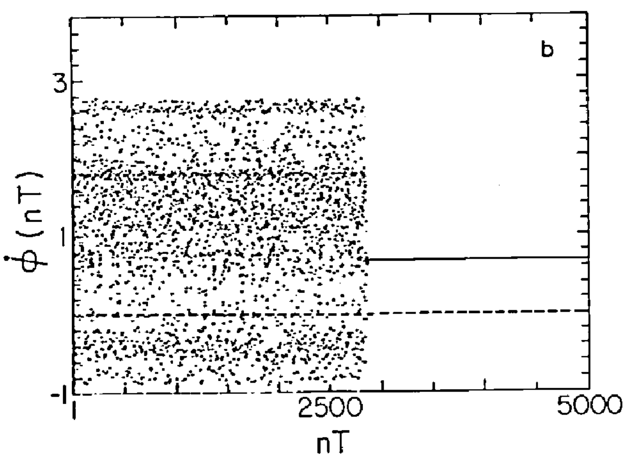


Fig. 6. Hard turbulence and pattern conversion. (a) Poincaré map $\phi_t(L/2,T)\, vs\, \phi(L/2,T) (\mathrm{mod}\, 2\pi)$ for the hard turbulent regime ($\rho = 0.7375$). (b) Strobed time series $\phi_t(L/2,nT)\, vs\, nT$ corresponding to a sudden pattern conversion after a long transient ($\rho = 0.8$).

At $\rho = 0.8$ the pattern formation and conversion mechanism underlying the hard turbulence regime, manifests in a striking way: the fluxonic (traveling-wave) can give rise to a localized breather-like oscillation locked to the driving frequency[8]. Fig. 6(a) presents the dynamical attractor that is suddenly removed after a long transient as is shown in Fig. 6(b).

5. SUMMARY

Soft turbulent behavior can be autonomously excited in the long Josephson junction, with a single oscillating drive. The spatiotemporal symmetry breaking, the spontaneous pattern formation and the ability of the system to sustain an spatiotemporal profile unlocked to the driving force determines the ability of the system to achieve the soft-turbulent regime.

In turn, pattern formation and conversion appears as the pervasive feature of the hard turbulent regime.

The route to soft turbulence begins with a period doubling bifurcation accompanied with pattern formation. This route differs from Feigenbaum's period doubling cascade as the control parameter is varied: the period 2 regime exhibits a direct transition to a two-frequency quasiperiodic regime and further increase of the control parameter destroys coherence in space. The knowledge of the differences between the onset of chaos and the onset of turbulence can provide a way to distinguish these two regimes in experimental situations.

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