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Dynamical analysis of turbulence in fusion plasmas and nonlinear waves ☆

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ABSTRACT

Turbulence is one of the key problems of classical physics, and it has been the object of intense research in the last decades in a large spectrum of problems involving fluids, plasmas, and waves. In order to review some advances in theoretical and experimental investigations on turbulence a mini-symposium on this subject was organized in the Dynamics Days South America 2010 Conference. The main goal of this mini-symposium was to present recent developments in both fundamental aspects and dynamical analysis of turbulence in nonlinear waves and fusion plasmas. In this paper we present a summary of the works presented at this mini-symposium. Among the questions to be addressed were the onset and control of turbulence and spatio-temporal chaos.

1. Introduction

In a oft-quoted remark, Richard Feynman called turbulence the most important unsolved problem of classical physics [1]. In fact a great deal of work and effort have been put over the past decades into obtaining a comprehensive description of the onset and development of turbulence in fluids, plasmas and waves [2–4]. Fluid turbulence plays an important role in the time evolution of many systems ranging from the planetary and stellar atmospheres to the boundary layers on airplanes and cars. Plasma turbulence became increasingly important in magnetic fusion research, where turbulence at the plasma edge is believed to play a key role for the transport of energy and particles [5].

These wide ranging applications turns difficult to obtain a precise definition of the physical meaning of turbulence. A rough definition is that a turbulent flow is disordered in both space and time scales, but this is far from being a mathematical definition. Moreover, there is a huge difference between one-, two- and three-dimensional turbulent flows, between fully-developed turbulence (where a statistical analysis is acceptable) and weak turbulence (where coherent structures dominate the flow). Instead of a precise definition of turbulence, we cite two common traits of turbulent systems [6]: (i) a turbulent flow must be unpredictable, i.e. a small uncertainty at a given initial time will amplify so as to render impossible a precise deterministic prediction of its evolution; (ii) it should be able to mix transported quantities much more rapidly than if elementary processes (such as molecular diffusion in fluids) were involved.

☆ This work is dedicated to the memory of the late Professor Liu Kai (1931–2010), one of the pioneers of nonlinear studies in Brazil and an inspired teacher of generations of physicists.

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One of the paramount questions in turbulence research is the onset of turbulence, i.e. where is the transition from a laminar flow to a turbulent flow, a question already posed in the work of Osborne Reynolds, as far back as in 1883 [7]. The mechanism underlying the onset of turbulence received attention of outstanding physicists and mathematicians like Heisenberg [8], Landau [9] and Kolmogorov [10]. A fresh approach to this subject was given by Ruelle and Takens in a seminal paper on the role low-dimensional chaos plays in the onset of turbulence [11]. The question of the onset of turbulence has been recently studied by many authors [12–14].

Given the widespread interest in both the phenomenology and theoretical ideas in the description of turbulence in fluids, plasmas and waves, we proposed a mini-symposium in the Dynamics Days South America 2010 Conference on this general theme. We have received contributions on some aspects of experimental and computational research on turbulence in a variety of physically relevant systems. The goal of this paper is to summarize the works presented in this mini-symposium.

In the second section we present results of electrostatic turbulence in fusion plasmas experimentally obtained from discharges in the Brazilian Tokamak TCABR. The experimental results are used for estimating parameters of a three-wave model presenting mode conversion. A theoretical approach to the onset of wave turbulence is greated in Sections 3 and 4 to a system of three nonlinearly interacting and resonant waves and a forced drift wave, respectively. In both cases, the onset of turbulence is related to dynamical changes in a low-dimensional chaotic attractor of the system.

Besides the topics outlined above, the mini-symposium talk by Prof. Phil Morrison, entitled "The Hamiltonian and Action Principle Formulations of Continua," must be mentioned. Because the problem of turbulence is so difficult, many reduced models have been constructed and studied. If one removes the dissipation and driving terms from such models, then it was proffered in this talk that the resulting reduced model should be Hamiltonian. To this end a general discussion of Hamiltonian and action principle formulations of continua, e.g. fluid and plasma models, was given [15,16]. Two procedures were discussed for constructing such formulations for reduced models: a procedure based on Hamilton's principle of mechanics, adapted for continua [17,18], and a procedure based on Poisson brackets that embody the appropriate symmetries sought in a model and a choice of energy function. This amounts to a Lie algebra realization with an appropriate algebra of invariants in terms of the observables of the model. Transformations between the formulations obtained by the two procedures were described in general and the particular examples of ideal magnetohydrodynamics [19] and Braginskii's fluid model with gyroviscosity [20,21] were discussed. Because the first procedure has been documented in the publications cited, it will not be further described here. The second procedure will be published elsewhere.

2. Electrostatic turbulence in the TCABR tokamak

Tokamaks are toroidal systems of magnetic confinement of plasmas, and are promising candidates to be the core of a future nuclear fusion reactor [22]. The usefulness of the tokamak as a fusion reactor relies, however, on its capability to maintain a sufficiently hot plasma during a time interval large enough to yield energy conversion. One of the factors conspiring against this ultimate goal is the loss of energy and particles through transport processes not yet fully understood, notwithstanding controlled. Electrostatic turbulence is the main cause of the anomalous particle and energy transport at the tokamak plasma edge [23]. Many experimental results suggest that electrostatic turbulence can be driven by Mirnov oscillations [24,25]. In particular, this influence has been observed in the Brazilian tokamak TCABR (Tokamak Chauffage Alfvén Brésilien), where the turbulent spectrum of the floating potential at the plasma edge has been observed to be affected by a magnetic mode created by an ergodic magnetic limiter [26–28].

In the TCABR the magnetic and electrostatic frequency spectra present a peculiar partial superposition, thus enhancing coupling, normally small, between these two kinds of fluctuations. Moreover, in some TCABR regimes the MHD activity increases at different instants of time during the discharge, and reaches high amplitudes with a narrow wave-number spectrum and a well-defined peak on the Mirnov frequency ($\sim$13 kHz) [29–31,31]. During this high MHD activity the electrostatic turbulence synchronizes with the MHD activity at the Mirnov frequency and its broadband wave-number spectra is greatly modified [31].

The hydrogen circular plasma of the TCABR tokamak has major radius R = 61 cm and minor radius a = 18 cm, with a maximum plasma current of 100 kA, with duration 100 ms, and toroidal magnetic field B_0 = 1.1 T. At the plasma edge the electron plasma density is $n_e \approx 3 \times 10^{18}\ \mathrm{m}^{-3}$, and the electron temperature is $T_e \approx 10$ eV [29]. The floating potential has been measured in the plasma edge and scrape-off layer regions ($0.9 < r/a < 1.2$) by a set of movable Langmuir probes. Magnetic fluctuations were measured by Mirnov coils located at $r/a = 1.08$.

In order to illustrate the coupling between magnetic and electrostatic oscillations we show in Fig. 1(a) the spectrogram of floating potential fluctuations, where the oscillation frequencies (in kHz) are plotted against the discharge duration, the corresponding power spectral densities $S_{\phi\phi}$ being plotted in a color scale. In Fig. 1(b) we depict the corresponding spectrogram for Mirnov oscillations, where the periods of magnetic activity are associated with peaks of the power spectral density S_{BB}. It is clearly seen a spontaneous increase of electrostatic activity following an increase in the magnetic activity, starting just before 40 ms with a dominant frequency of $\sim$13 kHz which extends up to 60 ms, with at least two overtones corresponding to higher harmonics of the dominant frequency. This clearly indicates a coupling between electrostatic and magnetic fluctuations and, moreover, a frequency synchronization between them.

In Fig. 1(c) and (d) we show the time series of the floating potential (normalized by its standard deviation) for two time intervals where the MHD activity is low and high, respectively. Comparing these series with the corresponding data for the