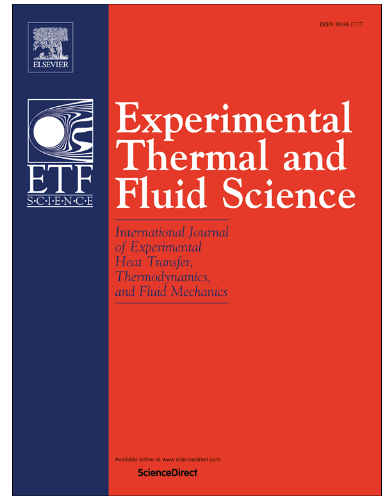

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ON THE CHAOTIC NATURE OF BISTABLE FLOWS

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Abstract. *Evidences from experimental measurements in tube banks submitted to turbulent cross flow in quadrangular and triangular arrangements show the presence of instabilities, being associated to the phenomenon of bistability, known in the simplified case of the flow on two cylinders side-by-side. Although not completely understood the study of the dynamic process of bistability can reveal new features about the chaotic behavior of these time series. As chaotic time series are observed routinely in experiments on physical systems, a study of the characteristics of bistability can be performed with the aid of techniques already established. This work presents a study about the determination of the Lyapunov exponents from experimental time series of bistable flows on the simplified geometry of two parallel circular cylinders and on a set of rows of a triangular tube bank. Time series of flow velocity and velocity fluctuations were obtained by means of the constant hot-wire anemometry technique in an aerodynamic channel. Discrete wavelet transform was used to make a multilevel decomposition of the series in several bandwidth values, accordingly with a selected decomposition level. Thus, the turbulence can be dissociated from the original signals, allowing a more accurate study to be conducted on the obtained state spaces. With these filtered time series, a state space reconstruction was performed by the method of time delays or Takens' method, while the percentage of false neighbors together with the embedding dimension were useful for the choice of some of the analysis parameters. The Rosenstein's method was applied to calculate the largest Lyapunov exponent of the time series. Easy to implement, this method is robust with respect to changes in most immersion parameters. Results show that the flow after two circular cylinders placed side-by-side and after two rows tube bank in triangular arrangement present positive largest Lyapunov exponents. This means that bistability has a clear chaotic behavior. In contrast, the flow after a five row tube bank is random.*

Keywords: *bistability; tube banks; hot-wire anemometry; deterministic chaos; largest Lyapunov exponents.*

1. INTRODUCTION

In 1899, Poincaré, studying the stability of the solar system through a variation of the so called "three-body problem", showed that the evolution of this dynamic system is often chaotic in the sense that small perturbations in its initial state, such as a slight change in the initial position of a body, will lead to radical changes in their future state (Poincaré, 1899). More generally, if an experiment performed in laboratory is not able to perceive small changes in the initial conditions of a dynamic system, for example, due to the uncertainties of the instruments used, then it is not possible to predict its final state. In this case and in simple terms, the dynamic system can be called as a chaotic system.

Examples of chaotic systems can be found in several areas of knowledge: in medical sciences, with the fractal structure of arteries and veins, in stem cell differentiation, in atrial fibrillation and in epileptogenic zone location (Higgins, 2002); in biosignals and medical image processing, with the analysis of respiration and heart rate variability (Semmlow and Griffel, 2014); in economy, with the study of financial time series, due to fact that random-looking variables may be deterministic chaos and predictable at least in the short-run (Adrangi *et al.*, 2008); in the study of electronic transport instabilities in semiconductors (Schöll, 2001); in turbulent flows with high Reynolds numbers, with the spatio-temporal behavior of fluid flows at large Reynolds numbers (Tsinober, 2009; Narasimha, 1987); and in the study of the weather, which makes its long-term prediction almost impossible to performed accurately (Lorenz, 1963).

In his study, Lorenz discovered that the simplified equations of convective rolls of atmosphere presented stable and unstable trajectories, contained within its own limiting area (central) or not (noncentral). These trajectories could also be classified as periodic, quasi-periodic and nonperiodic. This means that a relatively simple system of equations can result in a very complicated dynamic, leading to chaotic map that shows how the state of a dynamic system evolves over time in a complex pattern, not repetitive and whose form is known today as the "Lorenz attractor". It is a nonlinear system, three-dimensional and deterministic that exhibits chaotic behavior (Lorenz, 1963).

Ruelle and Takens (1971) defined the existence of what the Authors called "strange attractor", which is a graphical representation of the states of a system in phase space, which may arise when, in a closed trajectory, bifurcations occur as the magnitude of any parameter is changed.

In fluid flow, for sufficiently large Reynolds numbers, the motion can become very complicated, irregular and chaotic, with the onset of turbulence. In addition, the development and study of many strange attractors has been useful to analyze a variety of nonlinear systems, as in astronomy, turbulent fluid motion and in electrical circuits (Sprott, 2003).