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Saddle points and rare collisions under scaling approach in a Fermi accelerator with two nonlinear terms

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ABSTRACT

Rare collisions of a classical particle bouncing between two walls are studied. The dynamics is described by a two-dimensional, nonlinear and area-preserving mapping in the variables velocity and time at the instant that the particle collides with the moving wall. The phase space is of mixed type preventing diffusion of the particle to high energy. Successive and therefore rare collisions are shown to have a histogram of frequency which is scaling invariant with respect to the control parameters. The saddle fixed points are studied and shown to be scaling invariant with respect to the control parameters too.

1. Introduction

The traditional one-dimensional Fermi accelerator model consists of a classical particle of mass M which is confined to move between two rigid walls. One is fixed and works only as a returning mechanism for the particle to collides with the other one which is assumed to move in time. This simple system emerged as an attempt of Ulam [1] to model the original idea of Fermi [2] to describe the high energy measured from the cosmic rays. Indeed Fermi claimed that the energy of the cosmic particles could be gained from interactions of the particles with moving magnetic fields existent in the space. Therefore in Ulam's interpretation, the moving wall would indeed represent a moving magnetic field while the particle denotes a cosmic ray. The problem was that after the particle collides with moving wall and leaving the collision zone it moves with constant velocity to infinite. Ulam then imposed the existence of a fixed wall that the particle has to collide and returns for a further collision with the moving wall. The model as proposed failed to explain the cosmic rays high energy. The failure was due to the fact that the dynamics of the particle at high energy exhibits a short time elapsed between collisions leading to a strong correlation of them. The phase space which appears from the model is of mixed type showing both the existence of periodic islands (denoting regular/periodic motion) surrounded by a chaotic sea which is confined by a set of invariant KAM curves of quasi-periodic dynamics. Such a set of curves appear due to the high correlation between the collisions and they work as barriers that do not allow the particle to pass through, therefore setting an upper limit for the velocity growth.

The Fermi–Ulam model was considered after that in many different approaches, using different techniques and as motivation for several experiments [3–15]. The unlimited energy growth, the aim of the Fermi's idea would indeed be implemented if the returning mechanism of the particle for a next collision is changed. Pustylnikov [16] proposed replacing the fixed wall, which leads to correlation in the regime of high energy, to a gravitation field. Indeed, as soon as the particle accumulate energy from the collisions with the moving wall, the interval of time between collisions rises therefore leading to a lose of correlation between two collisions. For certain ranges of control parameters, the invariant KAM curves present in the phase space of the Fermi–Ulam are not observed in the Pustylnikov model. Depending on the combination of control

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parameters and initial conditions, the particle would exhibit diffusion in the velocity, leading to a phenomenon called as Fermi acceleration. However, either inelastic collision [17] and drag force [18] are shown to be sufficient conditions to suppress the unlimited growth of velocity therefore giving support to the assumption that Fermi acceleration is not a robust phenomenon [19]. It was shown in the literature that the introduction of drag force in the Fermi–Ulam model makes the particle loses energy (velocity) as it passed through a fluid such as a gas [20]. Depending on the initial conditions and control parameters, attractors were observed in the system including sinks and the behaviour around them were discussed.

In this paper we revisit the Fermi–Ulam accelerator model considering that the motion of the moving wall is given by a system of the type crank drive [21]. Our main goal is to understand and describe a specific type of rare collisions, namely as successive collisions, and the behaviour of the velocity of the saddle fixed points in the phase space. To do so, we use a scaling formalism. The dynamics of the model is described by a two-dimensional, nonlinear and area preserving mapping. The phase space is of mixed type and invariant KAM curves limit the energy gain of the bouncing particle. However in the limit of the radii of the crank approaching the length of the connecting rod, the movement of the moving wall becomes very fast for certain ranges of phase and very slow for others. In the limit case it may also lead to discontinuities in velocity of the moving wall therefore causing the particle to exhibit unlimited energy growth. However we will not consider such a range here.

The organisation of the paper is as follows. In Section 2 we present the model and discuss the variables and control parameters used. Our discussions regarding the rare events of the successive collisions are also described here together with the scaling for the saddle fixed points. Our conclusions and final remarks are presented in Section 3.

2. The model, numerical results and scaling formalism

In this section we revisited the model discussed in Ref. [21] aiming to understand and describe a set of rare collisions that the model exhibits, namely the successive collisions. Indeed the model describes the dynamics of a classical particle of mass M bouncing between two rigid walls. One of then is fixed at $x = \ell$ and the motion of the other wall is given by an equation of the type $s(t) = R\cos(\omega t) + \sqrt{L^2 - R^2\sin^2(\omega t)}$, where ω is the frequency of oscillation, R denotes the radii of the crank, L the length of the connecting rod. To define the initial conditions we consider that at the time $t = t_n$, the particle is at the position $x_p(t_n) = s(t_n)$ with velocity $v = v_n > 0$. Given the initial conditions, the dynamics may present two different kinds of collisions, such as: (i) a single hit with the moving wall or; (ii) multiple collisions with the moving wall. In the second case, the particle suffers a collision with the moving wall but, before it leaves the collision zone, which is defined as $x \in [-R, R]$, the particle has successive impacts with the moving wall. These impacts are rare in the dynamics and happen at the limit of low velocity. The probability of observing one successive collision is larger than observing two, that is larger than observing three and so on.

To write the mapping that describes the dynamics it is convenient to define dimensionless variables. We define $\epsilon = R/\ell$, $r = R/L$, $V_n = v_n/(\omega\ell)$ and measure the time in terms of the number of oscillations of the moving wall $\phi_n = \omega t_n$. We consider that the range for ϵ is $\epsilon \in [0, 1]$ and for r is $r \in [0, 1]$. The limit of $r \to 0$ corresponds to $L \to \infty$ and $r \to 1$ is obtained for $L \to R^+$. Using the new variables, we write the mapping as

$$T : \begin{cases} \phi_{n+1} = [\phi_n + \Delta T_n] \bmod (2\pi) \\ V_{n+1} = V_n^* - 2\epsilon\sin(\phi_{n+1})\left(1 + \dfrac{r\cos(\phi_{n+1})}{\sqrt{1 - r^2\sin^2(\phi_{n+1})}}\right), \end{cases} \tag{1}$$

where V_n and ΔT_n depend on the kind of collision. For the case where the particle leaves the collision zone, $V_n^* = V_n$ and $\Delta T_n = \phi_T + \phi_c$, where ϕ_T corresponds to the elapsed time the particle spends travelling from the last collision with the moving wall, up to suffering an elastic reflection with the fixed wall and being reflected backwards, therefore until the entrance of the moving wall. Thus, ϕ_T is given by

$$\phi_T = \frac{2 + \left(\frac{\epsilon}{r} - \frac{\epsilon}{r}\sqrt{1 - r^2\sin^2(\phi_n)}\right) - \epsilon\cos(\phi_n) - \epsilon}{V_n}. \tag{2}$$

The term ϕ_c is numerically obtained from $F(\phi_c) = 0$ for $\phi_c \in [0, 2\pi)$, where the function $F(\phi_c)$ is given by

$$F(\phi_c) = \epsilon\cos(\phi_n + \phi_T + \phi_c) + \frac{\epsilon}{r}\sqrt{1 - r^2\sin^2(\phi_n + \phi_T + \phi_c)} - \frac{\epsilon}{r} - \epsilon + V_n\phi_c. \tag{3}$$

For the case of multiple collisions with the moving wall, $V_n^* = -V_n$ and $\Delta T_n = \phi_c$ with ϕ_c obtained by the solutions of $G(\phi_c) = 0$ with $G(\phi_c)$ given by

$$G(\phi_c) = \epsilon\cos(\phi_n + \phi_c) - \epsilon\cos(\phi_n) - V_n\phi_c + \frac{\epsilon}{r}\sqrt{1 - r^2\sin^2(\phi_n + \phi_c)} - \frac{\epsilon}{r}\sqrt{1 - r^2\sin^2(\phi_n)}. \tag{4}$$

A solution of the function $G(\phi_c)$ for $\phi_c \in (0, 2\pi]$ is obtained numerically considering an accuracy of 10^{-12} and corresponds to a collision of the particle with the moving wall.