Chapter

Nonlinear Dynamics Phenomenon in a Polydyne Cam with an Offset Flat Faced Follower Mechanism with Clearance

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Abstract

Nonlinear response of the follower motion is simulated at different cam speeds, different coefficient of restitution, and different internal distance of the follower guide from inside. The nonlinear response of the follower is employed to investigate the chaotic phenomenon in cam follower system in the presence of follower offset. The numerical results are done using SolidWorks software. The chaos phenomenon is detected using Poincare' maps with phase-plane portraits, the largest Lyapunov exponent parameter, and bifurcation diagram. The largest Lyapunov exponent has a maximum values when the follower offsets to the right, while the largest Lyapunov exponent has a minimum values when the follower offsets to the left. The chaotic phenomenon in cam follower system when the follower offsets to the left is more than the chaotic phenomenon when the follower offsets to the right.

Keywords: chaotic phenomenon, follower offset, Lyapunov exponent parameter, nonlinear response. Poincare' maps

1. Introduction

The proposed system can be found in windshield wiper on the front window of the car in which the rotary motion of the cam transforms into an oscillating motion. Yang et al. introduced the mathematical model to describe the separation, transient impact, and contact in cam follower system using oblique impact, [1]. They showed that the cam and the follower system kept permanent contact without the use of coefficient of restitution at low speeds for the cam. Yousuf studied the detachment between the cam and the follower using largest Lyapunov exponent parameter, power density function of Fast Fourier Transform (FFT), and Poincare' maps due to the nonlinear dynamics phenomenon of the follower. Nonlinear response of the follower displacement is calculated at different cam speeds, different coefficient of restitution, different contact conditions, and different internal distance of the follower guide from inside [2, 3]. Flores et al. used a nonsmooth dynamics approach to model the interaction of the colliding bodies using Coulomb's law for dry friction [4]. Lassaad et al. studied the effect of cam profile error on the nonlinear dynamics behavior of oscillating roller follower system by using a model with eight degrees of freedom of two nonlinear Hertzian contacts [5]. Li and Du used the coefficient of restitution as a main control parameter to analyze the periodic movement and the bifurcation region in Non-fixed constrained collision vibration system [6]. Wu et al. studied the influence of the joint clearance on the dynamic response of a planar mechanism with two driving links and prismatic pair clearance under variable input speeds [7]. They concluded that the largest Lyapunov exponents are dependent on the clearance size and the input speed. Chen et al. identified the chaos phenomenon of the 2-DOF nine-bar mechanism with a revolute clearance using the phase diagrams, the Poincaré portraits, and largest Lyapunov exponent parameter [8]. Bifurcation diagrams with changing clearance value, friction coefficient, and driving speed are drawn. The aim of this paper is to discuss the chaotic phenomenon of an offset follower through the use of impact coefficient of restitution at different follower guides' clearances and different cam speeds.

2. Numerical simulation

Follower displacement is calculated using SolidWorks software [9]. The follower moved with three degrees of freedom. Four values of the follower guide's from inside (I.D. = 16, 17, 18, 19 mm) at different cam speeds are used. The follower with the offset (O = 20, 30, 40, 50 mm) are chosen. The impact coefficient of restitution with the values (0.2, 0.3, and 0.4) is considered in the calculation of nonlinear response of the follower in the presence of follower offset. Cam follower mechanism is shown in **Figure 1**.

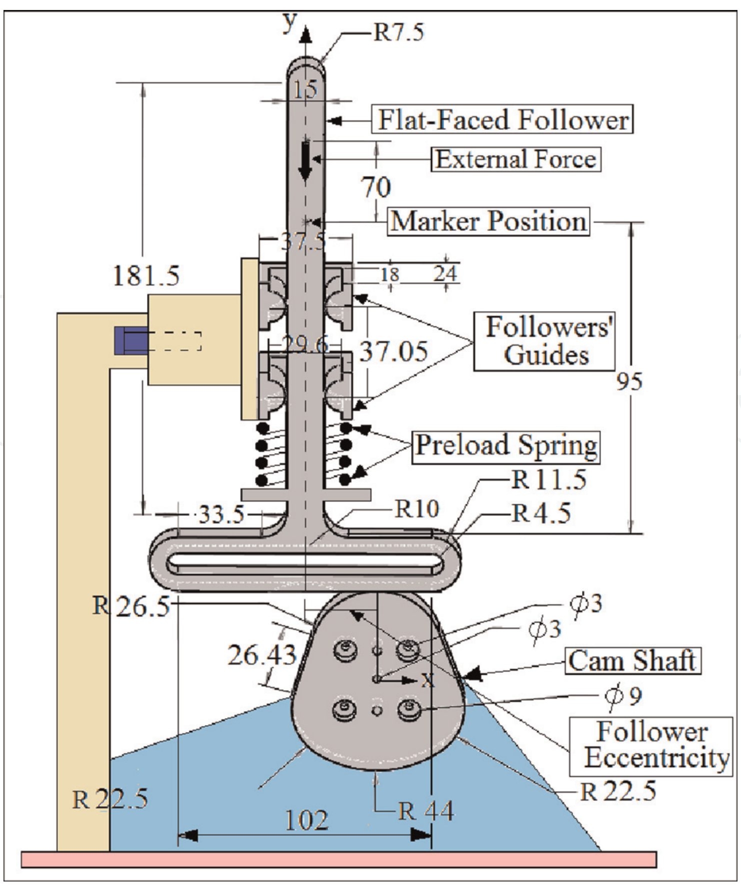

Figure 1.
Polydyne cam with an offset flat-faced follower.

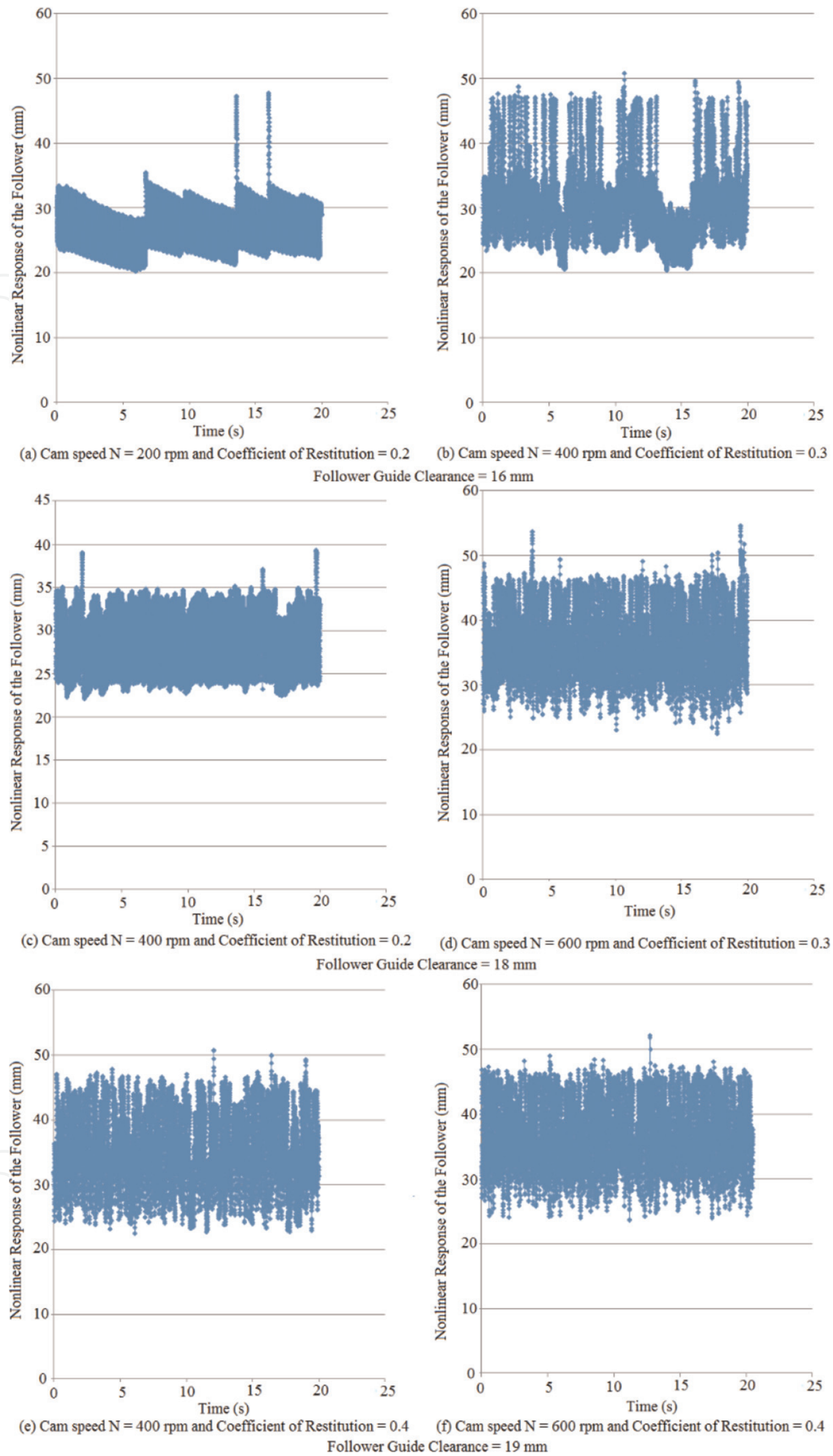

Figure 2.
Nonlinear response mapping when the follower offsets to the right (O = 10 mm).

The chaotic phenomenon in cam follower system is increased with the increasing of impact coefficient of restitution in which the impact will happen due the loss in potential energy of the follower and due to the increase in follower guide clearance value. **Figures 2** and **3** show the mapping of nonlinear response of the follower at

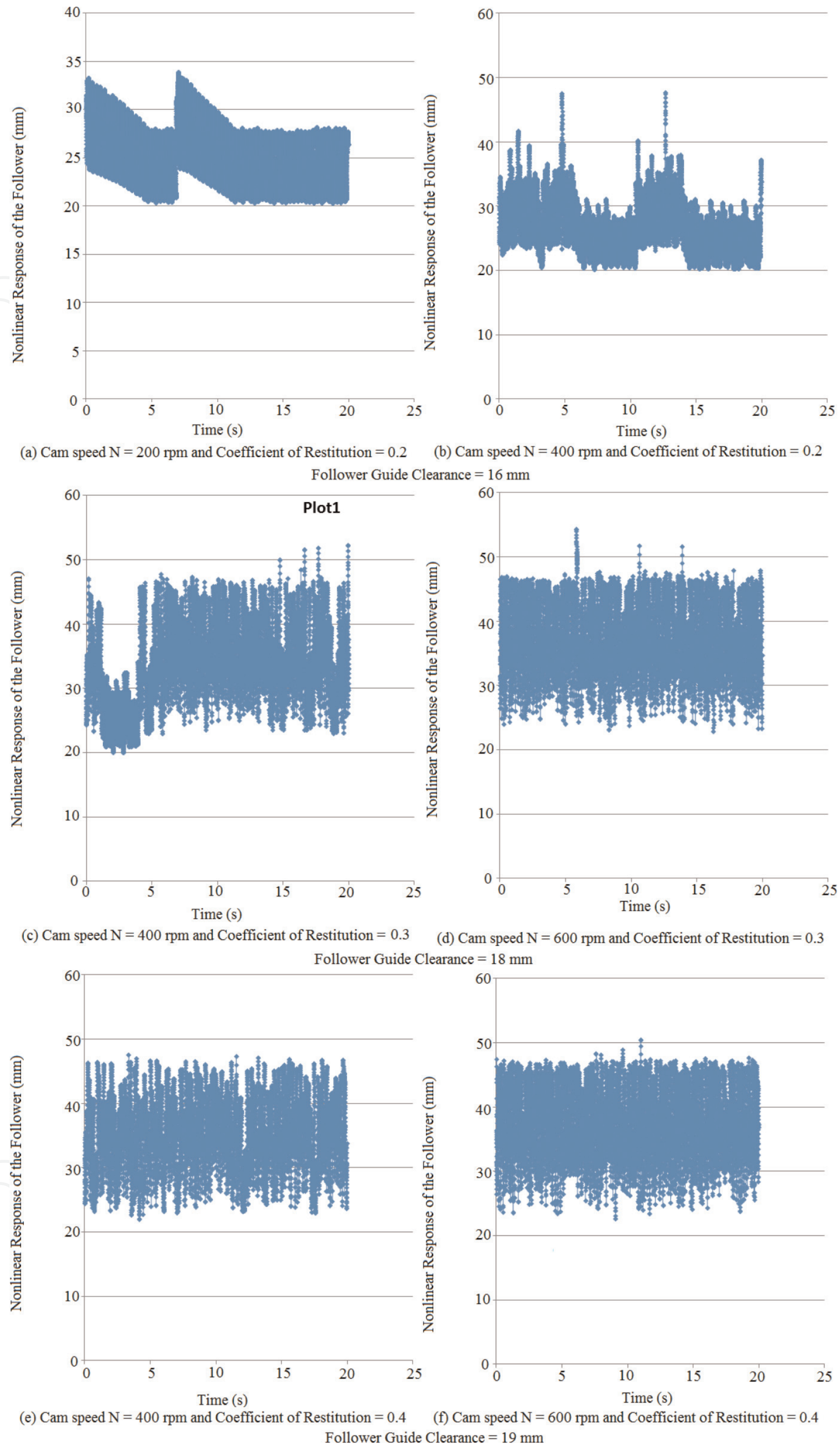

Figure 3.
Nonlinear response mapping when the follower offsets to the left (O = 10 mm).

different cam speeds, different follower guides' clearances, and different impact coefficient of restitution when the follower offsets to the right and left respectively (O = 10 mm). The nonlinear response of the follower is periodic as shown in **Figure 2a** and both the cam and the follower are in permanent contact. The follower lost the contact with the cam at time (t = 13.58 s) and (t = 15.99 s) at detachment height

DOI: http://dx.doi.org/10.5772/intechopen.106179

(26.98 mm) and (27.43 mm) respectively. Due to the coefficient of restitution, the follower keep bouncing from the cam from (t = 0.36 s) to (t = 5.658 s) while the follower will regain energy and keep permanent contact with the cam for the period from (t = 9.208 s) to (t = 10.11 s) which is having a periodic motion as illustrated in **Figure 2b**. The chaotic motion is shown in **Figure 2c–f** which increased with the increasing of follower guides' clearances, cam speeds, and coefficient of restitution. There is an intangible impact when the coefficient of restitution (0.2) and the dissipation in potential energy is occurred due to sliding while the contact is still valid between the cam and the follower, as shown in **Figure 3a**. The periodic and chaotic motion is together shown in **Figure 3b** and **c**. The periodic motion is shown from the period (t = 6.1 s) to (t = 10.26 s) and from the period (t = 14.14 s) to (t = 19.55 s) as shown in **Figure 3b** while the periodic motion begins from the period (t = 1.264 s) to (t = 3.808 s) as shown in **Figure 3c**. The chaotic motion is shown in **Figure 3d–f**.

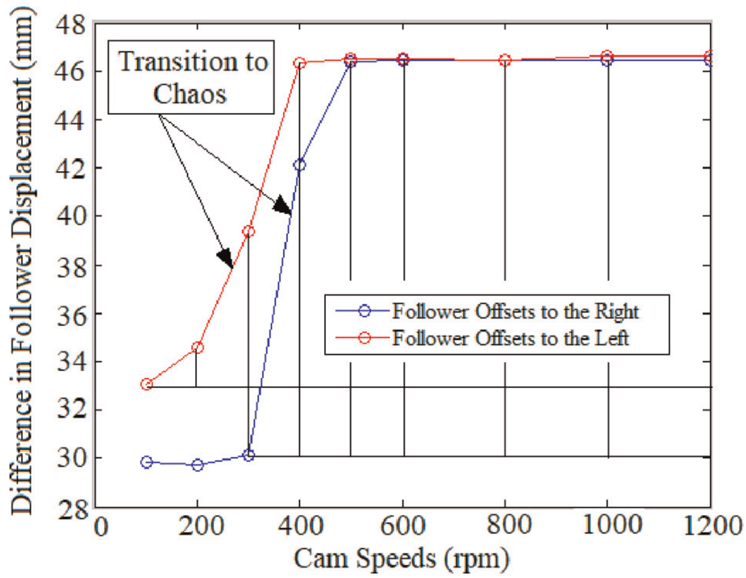

Figure 4.
Bifurcation diagram against cam speeds.

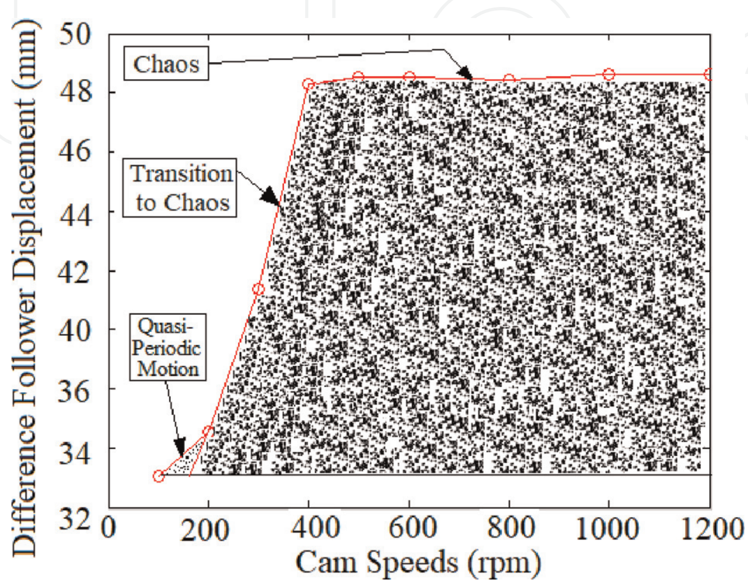

Figure 5.
Bifurcation diagram when the follower offsets to the left (O = 50 mm).

3. Bifurcation diagram

The contrast in angular displacement for the cam and the follower is used in the calculation of bifurcation diagram [10, 11]. **Figure 4** is built at the follower guide's from inside (I.D. = 19 mm) when the follower offsets to the right and left (O = 50 mm).

The periodic motion is shown in **Figure 4** in which it has the blue trend at cam speeds (N = 100–300 rpm) while the quasi-periodic motion of the follower has red trend at cam speeds (N = 100 rpm). The transition to chaos for the system when the follower offsets to the left is grown faster than the system when the follower offsets to the right as indicated in **Figures 5** and **6**. It can be concluded that the transition to chaos is incremented with the increment in cam speeds.

4. Lyapunov exponent parameter

Local Lyapunov exponent parameter is used to detect the chaotic phenomenon of nonlinear response of the follower attractor. Positive Lyapunov exponent refers to chaotic phenomenon while negative Lyapunov exponent indicates to periodic motion [12]. **Figure 7** shows the local Lyapunov exponent against number of points when the follower offsets to the right (O = 10 mm) at coefficient of restitution (0.2), cam speed (N = 200 rpm), and follower guide's clearance (16 mm). In this figure there are positive and negative local Lyapunov exponent in which the negative local Lyapunov exponent represents to the steady state while the positive local Lyapunov exponent reflects to the transient state. Each value of local Lyapunov exponent has a value of embedding dimension [13].

5. Poincare' maps with phase-plane portraits

The contact status of the follower is detected using Poincare' map at high and low speeds [14]. Moreover, the quantity of the black dots in Poincare' maps detects the

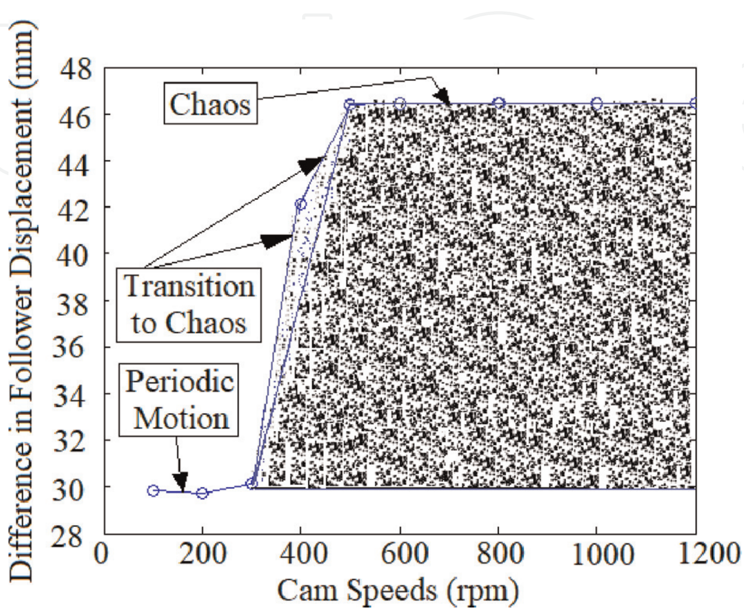

Figure 6.
Bifurcation diagram when the follower offsets to the right (O = 50 mm).

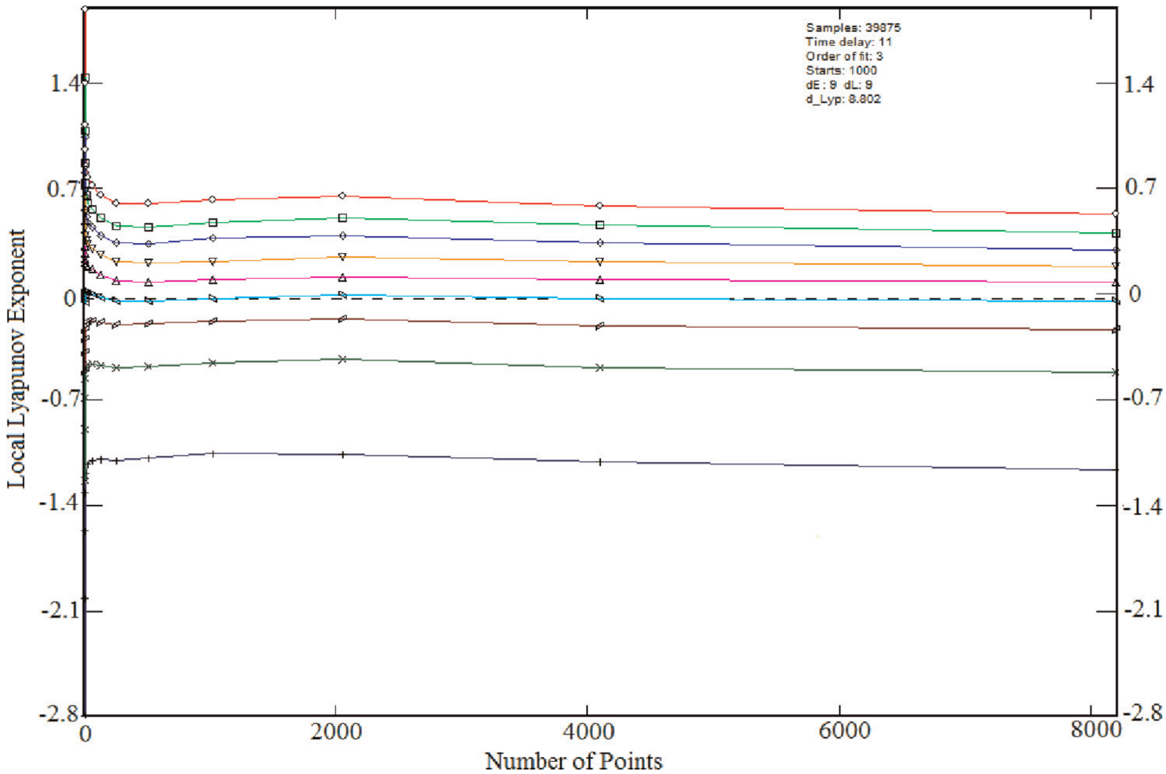

Figure 7.
Local Lyapunov exponent when the follower offsets to the right (O = 10 mm) at cam speed (N = 200 rpm), coefficient of restitution (0.2), and follower guide's clearance (16 mm).

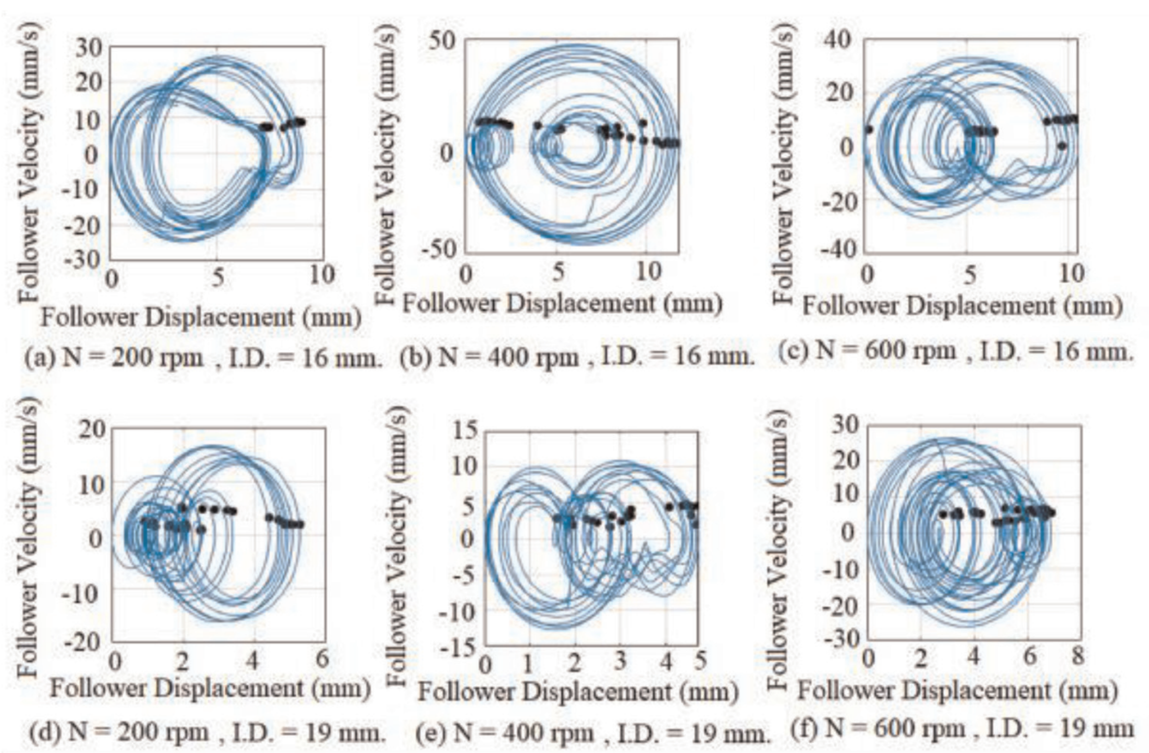

Figure 8.
Phase portrait of chaotic attractor when the follower offsets to the left (O = 20 mm).

chaotic analysis in follower movement when the follower has detached from the cam. The system in **Figure 8** has smooth orbit of follower displacement at (I.D. = 16 mm and 19 mm) when the follower offsets to the left (O = 20 mm) at diverse cam speeds.

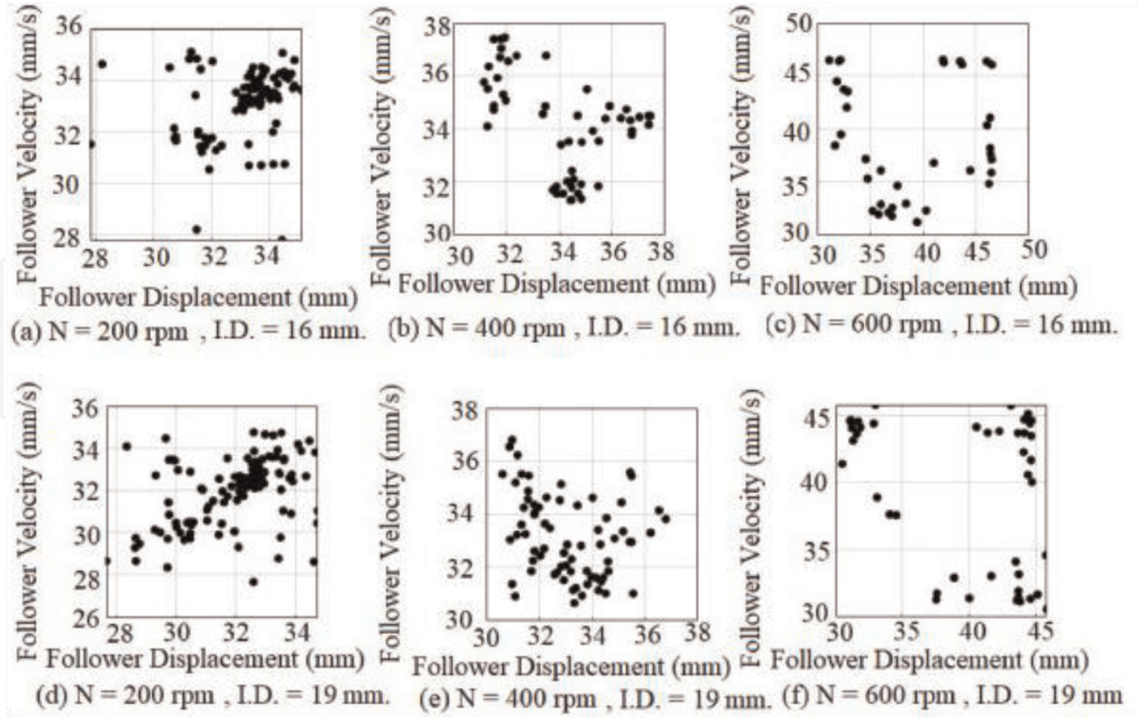

Figure 9.
Poincare' maps of chaotic attractor when the follower offsets to the left (O = 20 mm).

The follower displacement is repeated itself based on the single black dots in phase-plane orbit. The chaotic analysis is detected based on the multi black dots in phase-plane orbit at (I.D. = 16 mm and 19 mm) and diverse cam speeds as shown in **Figure 9**. SolidWorks software is used in the simulation.

6. Follower displacement

Figures 10 and **11** show the follower linear displacement against the time at different cam angular speeds when the camshaft offsets to the left (O = 40 mm) and to the right (O = 50 mm) at (I.D. = 17 mm) respectively. The follower stays in permanent contact when the cam starts spinning at (N = 200 rpm) and (N = 400 rpm), while the follower starts detaching from the cam at (N = 1000 rpm) as shown in **Figure 10**. The follower also starts jumping a little bit higher from the cam at (N = 800 rpm) as shown in **Figure 11**.

MATLAB Code:

The code algorithm of phase-plane diagram and Poincare' map are added at the end of this chapter. The code is done using MATLAB software and as in below:

```
clear; clc; close all
SignalName = '100rpm.dat';
signal = load(SignalName);
signal = signal - min(signal);
% Poincare map
% original D=signal; % Read data
[x1max,t1max] = findpeaks(D(:,1));
```

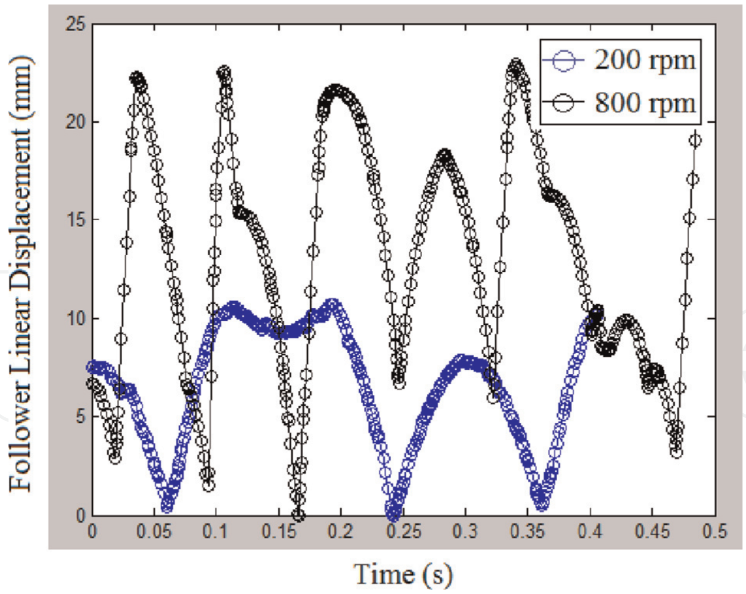

Figure 10.
Follower displacement against time when the follower offsets to the right (O = 50 mm) at various cam speeds.

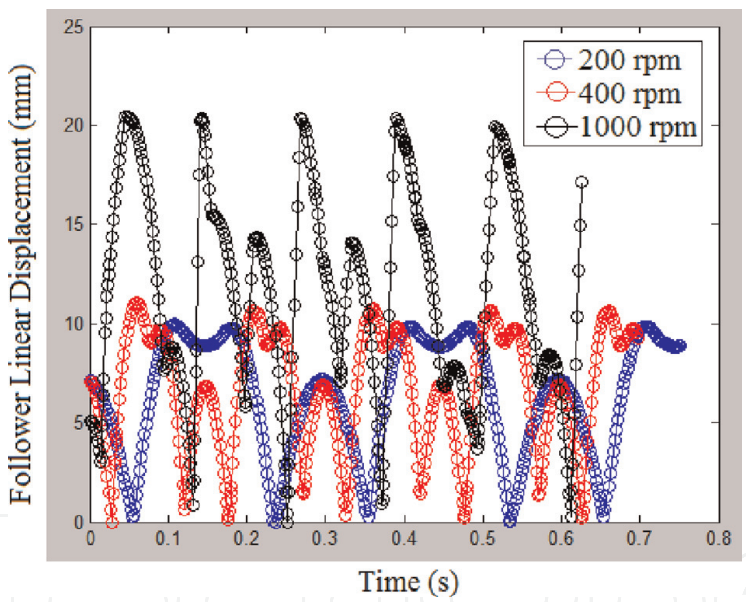

Figure 11.
Follower displacement against time when the follower offsets to the left (O = 40 mm) at various cam speeds.

```
Nmax = length(x1max); figure(1)
subplot(1,2,1)
for i=1:Nmax-1 plot(x1max(i),x1max(i+1),'ko','MarkerSize',5,'MarkerFa-
ceColor','k')
hold on
axis square
xlabel('x_{max} '),ylabel('next x_{max}')
grid on
end
%title('n = 100 rpm c = 1.5 mm') SignalName = '100rpmc2.dat';
signal = load(SignalName);
D = signal; % Read data
```

```
[x1max,t1max] = findpeaks(D(:,1));
Nmax = length(x1max); subplot(1,2,2)
for i=1:Nmax-1 plot(x1max(i),x1max(i+1),'ko','MarkerSize',5,'MarkerFa-
ceColor','k')
hold on
axis square
xlabel('x_{max} '),ylabel('next x_{max}')
grid on
end
%title('n = 100 rpm c = 2 mm') figure(2)
aa = load('100rpm.dat');
aa = aa - min(aa);
plot(aa, gradient(aa));
```

7. Conclusions

In this article the chaotic motion of the follower response is considered in the presence of impact coefficient of restitution using SolidWorks program. The chaotic motion of the follower response is occurred due to the increase in cam speeds, follower's offsets, follower guides' clearances and impact coefficient of restitution. The value of Lyapunov exponent is increased with the increasing of embedding dimensions values. The positive local Lyapunov exponent depicts the transient state in nonlinear response of the follower in the presence of impact coefficient of restitution. Negative local Lyapunov exponent refers to the steady state in the follower motion. Some of the nonlinear response of the follower has periodic and chaotic motions at different time periods. The quantity of the black dots in Poincare' maps detects the chaotic analysis in follower movement when the follower has detached from the cam.

Acknowledgements

The author wants to thank the editor and the reviewers for their helpful suggestion.

Conflict of interest

The author declares that he has no conflict of interest.

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