

Recurrence plot for parameters analysing of internal combustion engine

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Abstract. In many technical disciplines modern data analysis techniques has been successfully applied to understand the complexity of the system. The growing volume of theoretical knowledge about systems dynamic's offered researchers the opportunity to look for non-linear dynamics in data whose evolution linear models are unable to explain in a satisfactory manner. One approach in this respect is Recurrence Analysis - RA which is a graphical method designed to locate hidden recurring patterns, nonstationarity and structural changes. RA approach arose in natural sciences like physics and biology but quickly was adopted in economics and engineering. Meanwhile. The fast development of computer resources has provided powerful tools to perform this new and complex model. One free software which was used to perform our analysis is Visual Recurrence Analysis - VRA developed by Eugene Kononov. As is presented in this paper, the recurrence plot investigation for the analyzing of the internal combustion engine shows some of the RPA capabilities in this domain. We chose two specific engine parameters measured in two different tests to perform the RPA. These parameters are injection impulse width and engine angular speed and the tests are I11n and I51n. There were computed graphs for each of them. Graphs were analyzed and compared to obtain a conclusion. This work is an incipient research, being one of the first attempts of using recurrence plot for analyzing automotive dynamics. It opens a wide field of action for future research programs.

1. Introduction

Recurrence Plot Analysis (RPA) was introduced for the first time in 1987 in the paper published by Eckman, Kamhorst and Ruelle [1,2]. A recurrence plot (RP) is an advanced technique of nonlinear data analysis. It is a visualization (or a graph) of a square matrix, in which the matrix elements correspond to those times at which a state of a dynamical system recurs (columns and rows correspond then to a certain pair of times). The RP reveals all the times when the phase space trajectory of the dynamical system visits roughly the same area in the phase space [3].

The starting point is the idea that a measured time series is the result of the interaction between different relevant variables of a dynamic process. Each of that measured parameter is a one-dimension output of a multidimensional dynamic system. The method (RPA) infers characteristics of the original system and predicts its behaviour in the future given the history of its output. It analysed signal dynamics in reconstructed phase-space and reveals visual information about distance correlation between two points of attractor [3].



For examples, an internal combustion engine is a highly complex system with a large number of parameters that influence its dynamics. Engine angular speed, injection impulse width or vehicle speed could be considered realizations of that dynamical system. Our research was motivated by the desire to identify more intimate dependencies between outputs and inputs of the internal combustion engine.

In this respect we've conducted a large number of tests using more than 10 cars with 1.6 l petrol engine with mileage ranging 13500 to 115000 km. The experimental research program was designed to obtain a variety of data for defining the vehicle dynamics. Most of the experimental data were acquired and stored in the tester. Those which could not be measured using the on-board system were computed using static characteristics of the engine that had been obtained on the test bench [4, 5].

2. Method

2.1. Recurrence Plot

In this method, a one-dimensional time series from a data file is expanded into a higher-dimensional space, in which the dynamic of the underlying generator takes place. This is done using a technique called “delayed coordinate embedding”, which recreates a phase space portrait of the dynamical system under study from a single (scalar) time series [3].

Suppose that $x(i)$, $i=1, N$ is one of the time series that describes a dynamical system. The recurrence plot is an array of dots in a $N \times N$ square (a matrix), where a dot is placed at (i, j) whenever $x(j)$ is sufficiently close to $x(i)$ [1].

The elements of the matrix are defined as follows:

$$R_{jk} = H(\varepsilon - d_{jk}) \quad (1)$$

$$d_{jk} = \left\| \vec{V}_j - \vec{V}_k \right\|_2, \quad j, k = \overline{1, N} \quad (2)$$

Where: H is the Heaviside step function:

$$H(x) = \begin{cases} 0, & x < 0 \\ 1, & x \geq 0 \end{cases} \quad (3)$$

- ε is the threshold corridor, defined as a small percent from the standard deviation of initial time series (i.e. injection impulse width to be analysed, $i_j = i[j]$, $j = \overline{1, n}$);

- d_{jk} is the Euclidean distance between two vectors $\vec{V}_j - \vec{V}_k$;

$$R_{jk} = 1 \quad (4)$$

if and only if the state \vec{V}_j it is inside a “sphere“ of a radius ε , with \vec{V}_k as a center [2].

The phase space vectors are reconstructed according to Taken's time-delay embedding theorem [2, 6], from univariate time series $i[1], i[2], \dots, i[1]$, (i.e., n – successive quantized samples of injection impulse width, measured from some appliance):

$$\vec{V}_j = (i_j, i_{j+\tau}, \dots, i_{j+(m-1)\tau}) \quad (5)$$

where: j is the time index; m is the embedding dimension; τ is the time delay.

The number of vectors N , is computed as follow:

$$N = n - (m - 1)\tau \tag{6}$$

where N is the horizontal/vertical dimension of recurrence matrix.

Embedding dimension m should be large enough to unfold the system trajectories from self-overlaps, but not too large, otherwise the noise will amplify. The rule of thumb is to set m to

$$m \leq 2N + 1, \tag{7}$$

where N is the number of operating variables, or degrees of freedom, in the dynamical system under study. One analytical method for estimating the embedding dimension is the False Nearest Neighbors method [7].

Choosing the optimal time delay is not an easy problem. If it is too long, the coordinates may become random in respect to each other, or it is too short, the coordinates used for each reconstructed vector will not be independent enough to carry any new information about the trajectory of the system in the state space. Usually, for estimating the time delay is used Mutual Information Function [7].

Each element of the square matrix, called recurrence matrix will receive a pixel, black or white, and will be displayed in a monochrome digital image, which is recurrence plot [2]. Also, the distances between all vectors are mapped to colors from the pre-defined color map and are displayed as colored pixels in their corresponding places. A recurrence plot is essentially a graphical representation of a correlation integral. The important distinction is that it, unlike the correlation integrals, preserve the temporal dependence in the time series, in addition to the spatial dependence [7].

The next step and most difficult and interesting in the same time, is to interpret the plot. Large-scale structures (typology) and small-scale patterns (texture) can be easily detected [1, 2, 8]. The topology can be characterized as homogeneous, periodic, drift, and disrupted. Texture can be classified in single/isolated dots, diagonal, horizontal/vertical lines, rectangular clusters [2]. If the underlying signal is truly random and has no structure, the distribution of colors over the RP will be uniform, and so there will not be any identifiable patterns. If, on the other hand, there is some determinism in the signal generator, it can be detected by some characteristic, distinct distribution of colors. The length of diagonal line segments of the same color on the RP can give you an idea about the signal predictability [7].

2.2. Recurrence plot for analysing internal combustion engine parameters

To be analysed, there were chosen injection impulse width and engine angular speed. Each of them is dependent of an unknown number of other parameters with a statistical variation. The first set of data was collected from a vehicle with a millage of 95000 km (I11n) and the second from one with a millage of 33800 km (I51n). The idea was to compare parameters of engines with different wear.

Table 1. Embedding dimension and Time delay.

		Embedding dimension m	Time delay n
Test I11n	Injection impulse width	5	6
	Engine angular speed	10	12
Test I51n	Injection impulse width	5	6
	Engine angular speed	7	5

First, we used the mutual information function and false nearest neighbors method to estimate the time delay and the embedding dimension for each parameter and test.

Figure 1 and figure 2 presents the results for choosing the embedding dimension and time delay of injection impulse width for test I11n, $m=5$ and $n=6$.

Table 1 shows the results for embedding dimension and time delay of injection impulse width and engine angular speed for tests I11n and I51n. As a first conclusion, injection impulse with seems to be more deterministic variable than the engine angular speed.

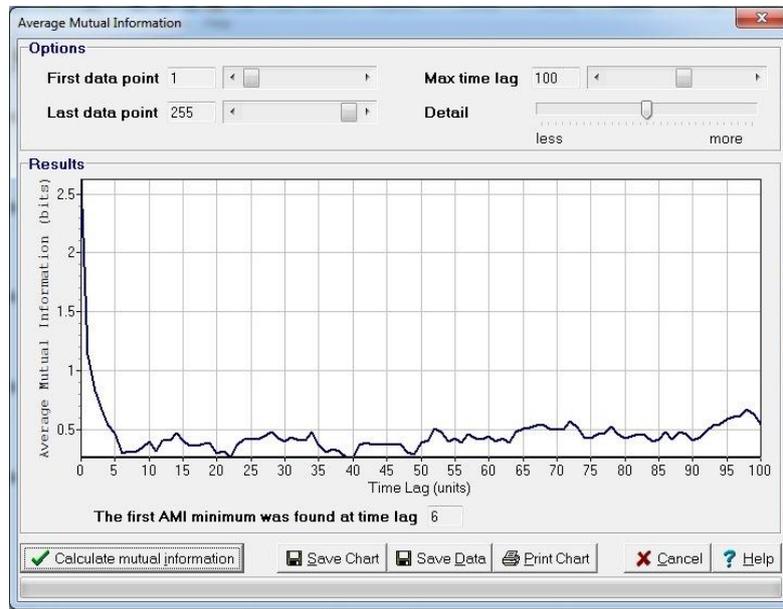


Figure 1. Average Mutual Information of injection impulse width, Test I11n.

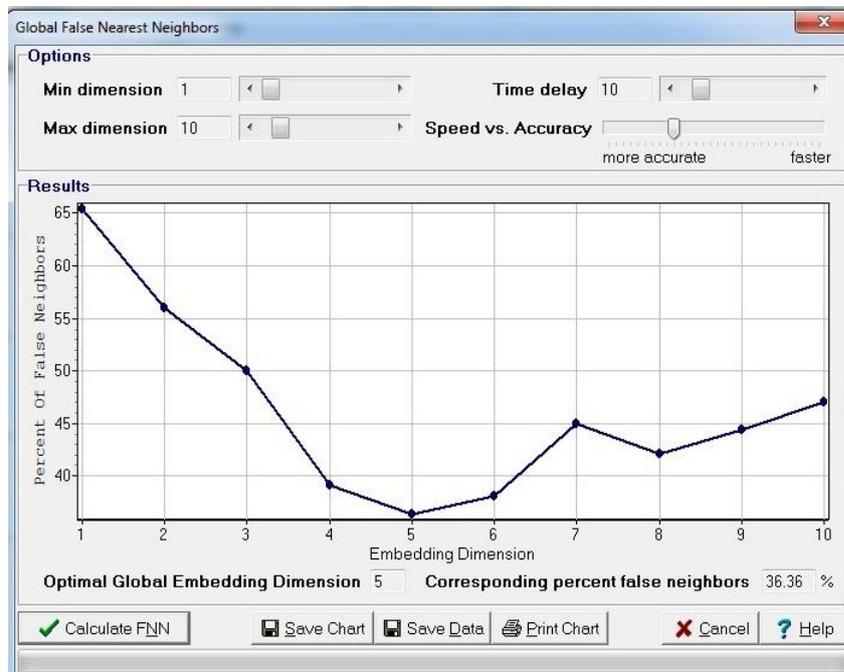


Figure 2. Global False Nearest Neighbors of injection impulse width, Test I11n.

Also, deterministic nature of injection impulse width is confirmed by the figure 3 and figure 4. There are some diagonal lines with evolution of states similar at different times that prove it. Similarities cannot be observed in recurrence plot of engine angular speed in figure 6 and figure 10. As it is known, electronic control unit sets the impulse injection width based on few deterministic

variables, while the angular engine speed is more influenced by stochastic sizes. All processes analysed are non-stationary, none of plots presents homogeneity.

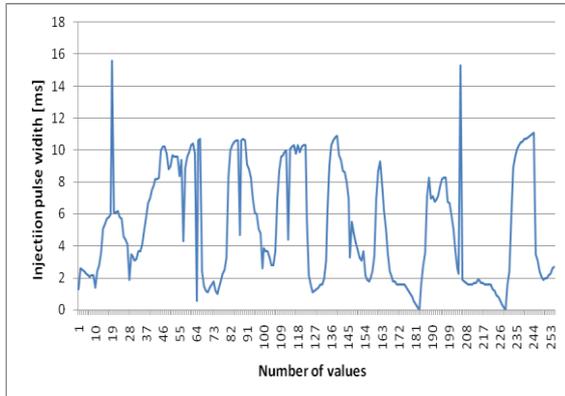


Figure 3. Injection impulse width, test I1 In.

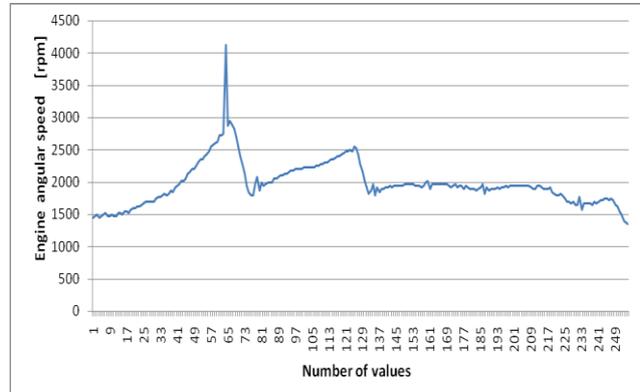


Figure 4. Engine angular speed, test I1 In.

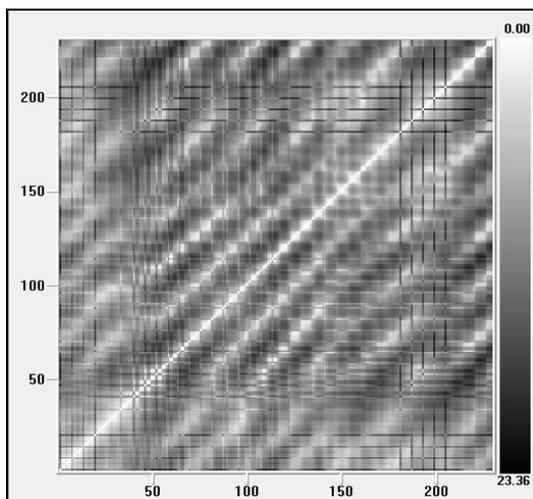


Figure 5. RP of injection impulse width, I1 In.

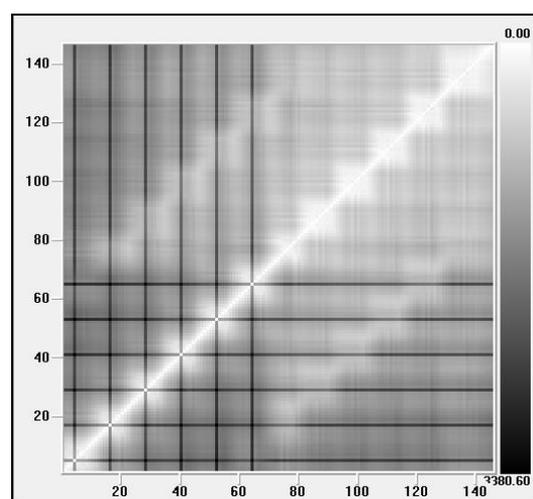


Figure 6. RP of engine angular speed, I1 In.

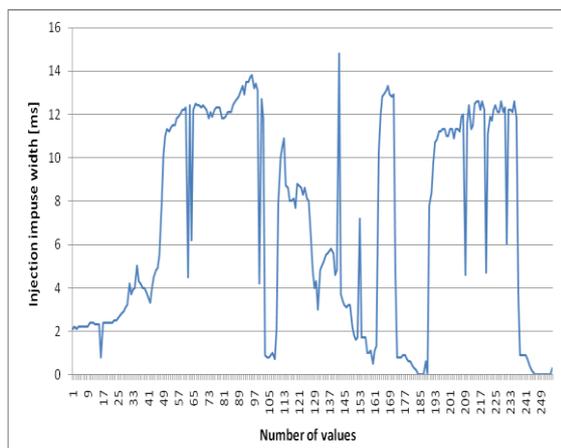


Figure 7. Injection impulse width, test I5 In.

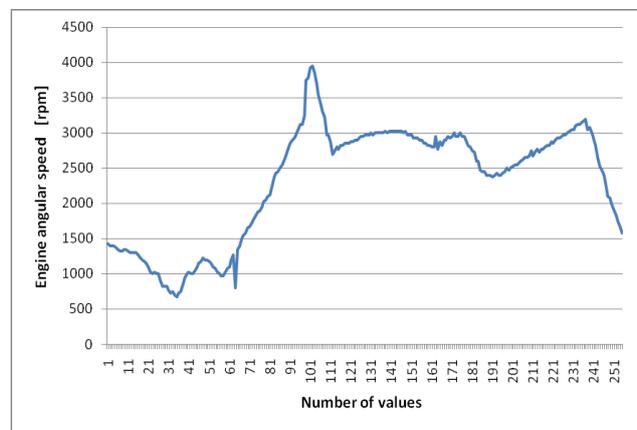


Figure 8. Engine angular speed, test I5 In.

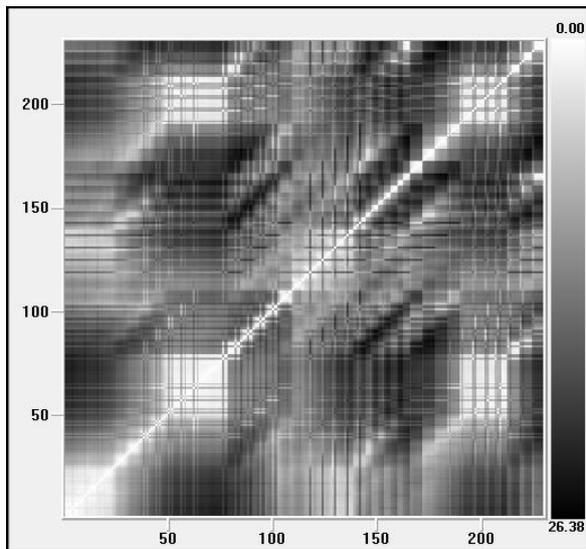


Figure 9. RP of injection impulse width, I51n.

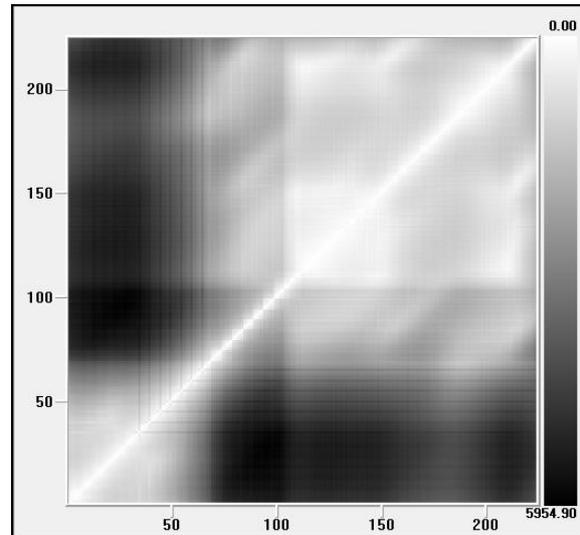


Figure 10. RP of engine angular speed, I51n.

3 Conclusions

This paper one of the first attempt of using recurrence plot for analyzing automotive dynamics. Yet, even if it is mostly a qualitative tool, recurrence plot is extremely powerful and useful in analysing dynamical systems. To accomplish a qualitative recurrence plot analysis, a quantitative approach has to consider. Future developments could lead to recognition of each engine based on graph obtained by this method. Also, it could be used to perform an extremely sensitive diagnose of vehicle systems. There is a vast field of applications for using this method in automotive.

References

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