TIME SERIES SPACE PHASE QUALITATIVE ANALYSIS AND A POSSIBLE APPLICATION

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ABSTRACT: In a coherent light scattering experiment using a laser beam and a cuvette containing a suspension the interference field has a boiling speckle aspect. Using a detector and a data acquisition system a time series can be recorded. A possible definition for the space phase of a time series is defined. The distribution of the velocities and the trajectory in the phase space are analyzed both for computer simulated samples and for recordings on two suspensions that have the average particle size measured using Dynamic Light Scattering procedure. The results reveal that the distribution of the velocities and the trajectory in the phase space can be used in a qualitative way to characterize the average particle size in suspension.

KEY WORDS: time series, phase space, velocity distributions, suspensions

1 INTRODUCTION

If coherent light is incident on a medium with SC a non-uniformly illuminated image is obtained, currently named speckled image, having a statistical distribution of the intensity over the interference field. The speckled image appears as a result of the interference of the wavelets scattered by the SC, each wavelet having a different phase and amplitude in each location of the interference field. The image changes in time as a consequence of the SC complex motion, both of sedimentation and of the Brownian motion (Chicea, 2008, a), (Chicea, 2014), (Chicea & all, 2010. This complex motion produces fluctuations of the image intensity in each location of the interference field, giving the aspect of "boiling speckles".

The speckled image can be observed either in free space and is named objective speckle or on the image plane of a diffuse object illuminated by a coherent source and it is named subjective speckle (Goodman, 1984).

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The review paper (Briers, 2001) names the two types of speckled images as far field speckle and image speckle. In this work the objective speckle, respectively the far field speckle is considered, recorded and analyzed. Although light propagation through disperse systems such as biological cells in suspensions or grouped in tissues has been studied extensively, especially using image processing techniques (Briers, 2013), (Chicea, 2007) the scattering process modeling and characterization is not straightforward.

Recording the far field fluctuations on a certain location using a detector and a data acquisition system will produce a time series. Time series have been extensively analyzed using different procedures.

A widely used class of procedures start with the Fourier transform to produce the PSD. The shape of the PSD depends of two parameters. Finding them using a least squares fit will provide information on the size and size distribution of the particles in suspension.

Just some of the papers that describe in detail and report results found using the above mentioned procedure, currently named DLS, are (Chicea, 2012, a), (Chicea, 2009), (Chicea, 2010), (Chicea & all, 2012), (Chicea, 2013).

An alternative procedure to analyze time series, whether produced by a detector and a data acquisition system in a light scattering experiment or extracted from a recording using a CCD (Chicea, 2008, b), in a qualitative manner, using the patterns of the time signal in the space phase, is presented in the next section.

2 THE PHASE SPACE

The PS is the collection of all states for a system. A time series is actually a vector *x(i), i=1÷n,* containing the collection of values, intensity if we record a far interference field in a light scattering experiment, and n is the total number of recorded values. Typically, the values are recorded at equal time intervals, $\Delta t=1/fs$, where *fs* is the sampling rate of the data acquisition system. We can define a velocity at time t, hence corresponding to the value *x(i)* of the time series, as the variation rate of the time signal at that moment:

$$v(i)=\frac{x(i+1)-x(i)}{\Delta t} \quad (1)$$

We therefore find a pair of *[x(i), v(i)]* for each value in the time series, a total of n-1 pairs. Each pair represents a point in the 2 dimensional space, which we can define as the space phase (SP) for the time series.

First a simple algorithm to generate in a realistic manner time series that were recorded during a DLS experiment was established. A time series, as results from the Fourier analysis of the recorded data (Chicea, 2012, a), (Chicea, 2009), (Chicea, 2010), (Chicea & all, 2012), can be modeled as an overlapping of harmonic functions of different frequencies. Moreover, the smaller the particles in suspension are, the bigger the turnover point is (Chicea, 2012, a) in the PSD. With these facts in mind, a program to generate the time series with a sampling rate *fs* was written and used.

The program generates a certain number n_f (50 for the work reported here) of amplitudes a_i in the range (Chicea, 2008, a), using a uniform random distribution, with a random initial seed, computed using the system clock. It also generates n_f frequencies f_i in the range [f_1, f_2] and initial phases φ_i in the range [0, 2π] and the vector containing the moments t_i with the desired number of values, equally spaced at Δt. Each value x_i is computed using equation

$$x(i)=\sum_{j=1}^{n_f} a_j \cdot \sin\left(2\pi f_j \cdot t_i+\varphi_j\right) \quad (2)$$

(2)

In (Chicea, 2012, a), (Chicea, 2009), (Chicea, 2010), (Chicea & all, 2012), (Chicea, 2013) it is stated that the smaller the particles are, the bigger the frequencies are, therefore an attempt to simulate experimentally recorded time series for different particles in suspension must have different frequency ranges. Several time series were used in the simulation presented in this work and two of them were selected.

We call the first s1, having the 50 frequencies generated in the range 100-200 Hz and the second s2 with the frequencies in the range 2000-2500 Hz. Each series lasted for 2 seconds and *fs* was 10000 Hz, thus having 20000 values each.

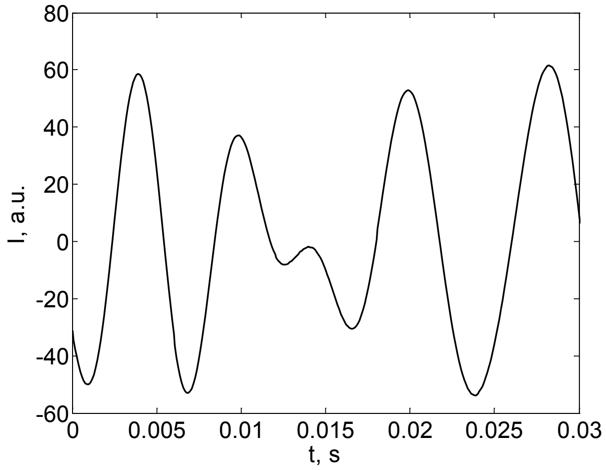

Figure 1. A 0.3 s sequence of time series s1.

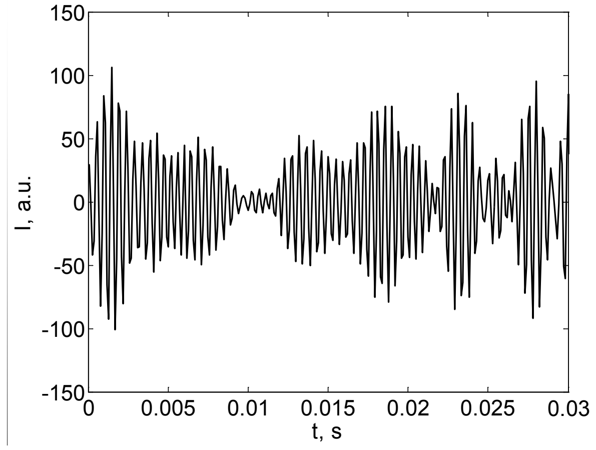

Figure 2: A 0.3 s sequence of time series s2.

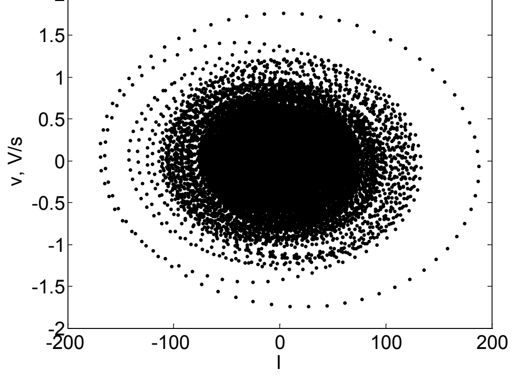

Figure 3. The PS for s1.

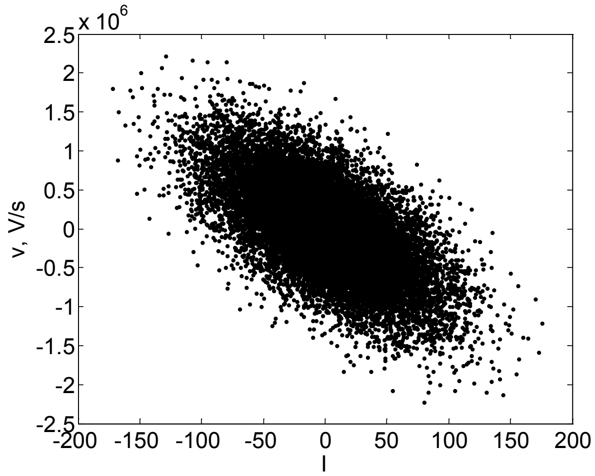

Figure 4. The PS for s2.

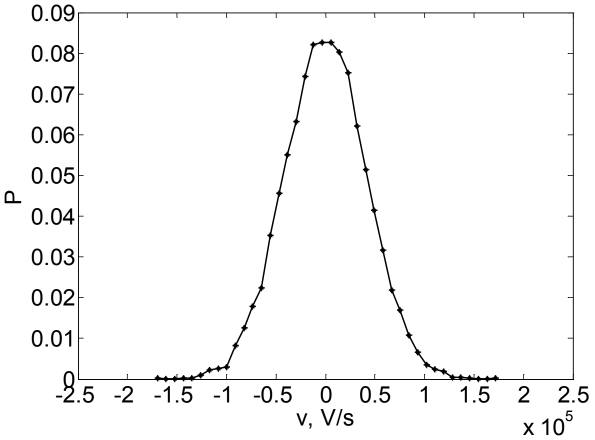

Figure 5. The distribution of the velocity values v, in SP, for s1.

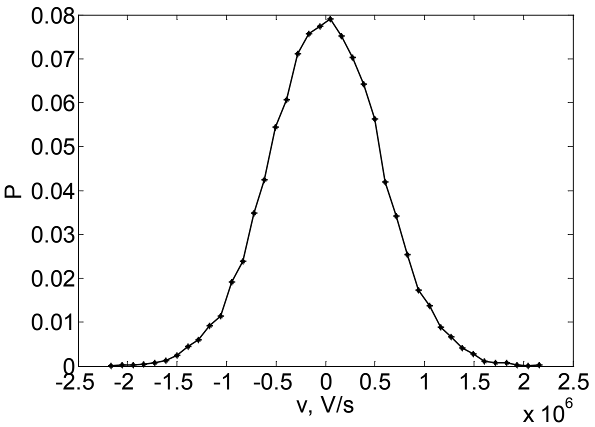

Figure 6. The distribution of the velocity values v, in SP, for s2.

A plot of a 0.03 s sequence of the time series s1 is presented in Fig. 1 and of the time series s2 in Fig. 2. Figs. 1 and 2 reveal a faster variation of the s2 time series than in s1, as expected. The PS of the two time series, s1 and s2 is presented in Figs. 3 and 4.

We notice the big difference in the PS shape. S1 that contains slower fluctuations is elliptic closer to a circle for this axes range selection while s2 that contains faster fluctuations is a prolonged ellipsis.

The distributions of the velocity values v, in SP, for the two series, were calculated with equation (1). Fig. 5 presents the distribution of the velocity values v, in SP, for s1 and Fig. 6 distribution of the velocity values v, in SP, for s2.

Examining Figs. 5 and 6 we notice the difference between the two distributions, laying in being wider for the s2 time series that containing faster fluctuations.

Moreover, we notice that the distribution is symmetrical in both situation and the resemblance with the Gaussian is very good.

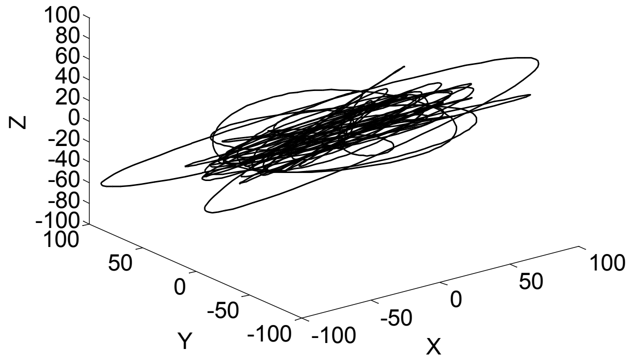

Figure 7. The 3D trajectory in the SP for s1, delay 50 recordings

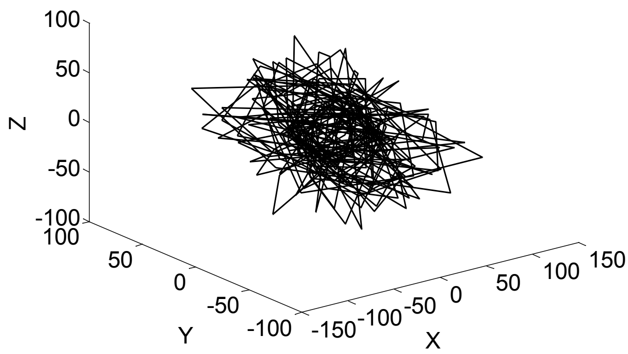

Figure 8. The 3D trajectory in the SP for s2, delay 50 recordings

If we introduce a delay of a certain number of recordings in the time series for the y coordinate and a double delay for the z coordinate a 3D trajectory of the system in the SP can be plot. A delay of 50 recordings was used and the trajectory in the SP for s1 and for s2 are plot in Figs. 7 and 8. Examining the plots we notice again significant differences between the trajectories.

The trajectory for s1 is smooth and prolonged, aligned to a direction while for s2, with faster fluctuations, appears to present rough turns and does not appear to be oriented to a certain direction.

3 RESULTS AND DISCUSSION

The results of the qualitative analysis presented in the previous section were compared with experimental results.

A water sample from a river was extracted after a heavy raining and was analyzed using the DLS procedure described in details in (Chicea, 2012, a), (Chicea, 2009), (Chicea, 2010), (Chicea & all, 2012), (Chicea, 2013).

The DLS results reveal that the average diameter was 0.134 μm. We name this time series rw1. After 24 h the sample was analyzed again and the average diameter was found to be 0.635 μm. We name this time series rw2.

The average diameter increased because the inorganic suspensions, like sand and silt, which have the bigger concentration and the smaller diameter, became sediment. The organic particles having the density closer to the water density remained suspended during the experiment.

Figure 9 reveals the PS for the experimental rw1 time series and Fig. 10 for the experimental rw2 series having bigger particles in suspension. Examining the two imagines we notice that the PS of rw1 appears to have more domains, as there are at least two groups of particles in suspension, the inorganic particles, having bigger density and the organic particles, which remained suspended.

The other feature of the PS is that it presents differences in the velocity distribution. The distribution of the velocities of rw1 are presented in Fig. 11 and of rw2 time series recorded during a DLS experiment are presented in Fig. 12. Examining the velocity distributions we notice that the distribution of rw2 is wider than the distribution of rw1.

Moreover, we notice that the distributions cannot be viewed as a simple Gaussian distributions but as a complex overlap of several distributions and this can be the result of the fact that the particles in suspension, both in rw1 and rw2 have a complex size distribution rather than a mono dispersed distribution, therefore the simple observation from Fig. 5 does not stand in all situations.

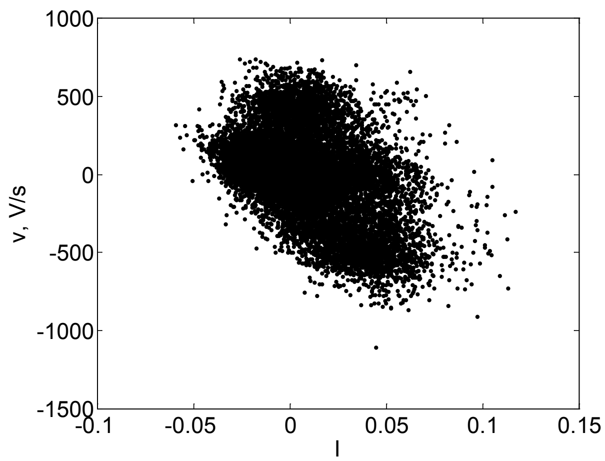

Figure 9. The PS for rw1.

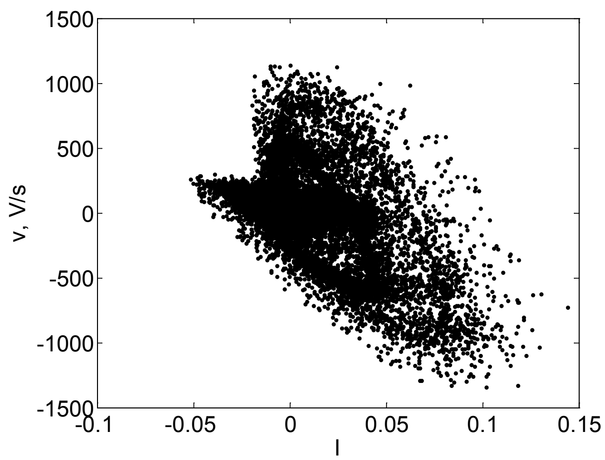

Figure 10. The PS for rw2.

4 CONCLDING REMARKS

The PS was defined for a time series as the collection of all possible states. Several time series were generated using a computer code written for this purpose. The time series were the sum of 50 harmonic functions with random amplitudes, phases and frequencies, the last being generated in a certain interval.

Two series with frequencies in the intervals [100 – 200] Hz and [2000 – 2500] Hz were generated starting from the assumption that the frequency of the fluctuations in a DLS time series strongly depends of the suspended particle size.

A scatter plot in the PS and a velocity distribution are presented for each of the two samples, together with the trajectory in the SP.

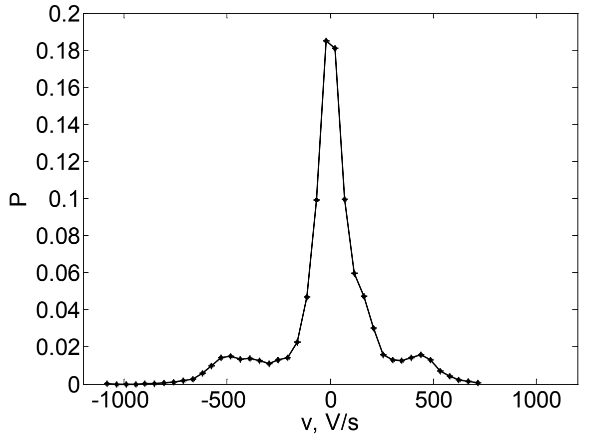

Figure 11. The distribution of the velocity values v, in SP, rw1.

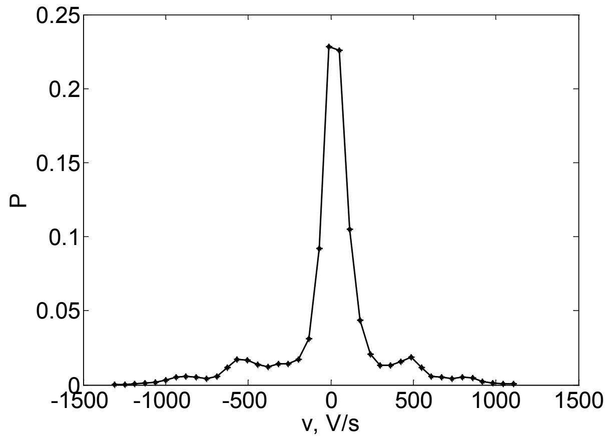

Figure 12. The distribution of the velocity values v, in SP, rw2.

The simulation reveals that the plot of the PS can give a qualitative image about the particles assumed to be in suspension.

The smaller the particles are and the narrower the particle size distribution is (reflected in smaller frequency range), the more prolonged the image in the PS is. Moreover, smaller particles (hence bigger frequencies) produce a wider velocity distribution. A narrow frequency interval produces a symmetrical distribution resembling very well a Gaussian.

These qualitative conclusions are confirmed in part by the results of the same procedures applied on experimentally recorded time series during a DLS experiment.

Using the two river water samples, we found the shape of the image of the PS appears to exhibit different domains if there are more types of particles in suspension. And more, the velocity distribution appears to be the sum of several distributions, under the same circumstances.

These conclusions suggest a simple procedure that can be used in monitoring the evolution of the particle size in a suspension, as in sedimentation of particles in rivers, colloid aggregation or biological fluids.

The shape of the space phase and the width and shape of the velocity distribution can provide qualitative information on the distribution of the average suspended particle diameter.

Work is scheduled to simulate the time series in a more realistic manner, considering a complex size distribution of the suspended particles.

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6 NOTATION

The following symbols are used in this paper:
PS = phase space
SC = scattering centers
PSD = power spectrum density
DLS = Dynamic Light Scattering
CCD = charged coupled device