An interactive visual interface for the determination of similarity patterns in the Fourier spatial frequency spectrum of laser speckle

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ABSTRACT

Laser speckle from particles that are smaller than the wavelength of light resemble a random Gaussian field, but can be shown to contain a characteristic spectrum in frequency space. Speckle is caused by not only the instantaneous micro-structure of nanoparticles in suspension that will fluctuate as they reorganize, but also by the magnetic and optical properties of the scattering medium itself. Here we demonstrate interactive tool that can be used to define similarities between seemingly random scattering fields. Optimization of the Fourier spatial frequency spectrum gives a representative pattern that can be directly correlated to the transport properties of the particles.

Keywords: Laser speckle, Fourier spatial frequency analysis, image analysis, nanoparticle

1. INTRODUCTION

A central issue in the comparison of 2D imaging planes is the definition of similarity. Image processing methods typically focus on identification and characterization of visual elements, such as the size, shape, and regularity of objects or image templates, and develop similarity metrics to evaluate a best math by a numerical score[1]. Comparison between different images is made by a statistical analysis to determine if the quantification metrics of the images lie within an acceptable standard error of each other. Fourier space methods have also been developed, and may show promise for future development. Wavelet analysis applies a filter that is drawn from Fourier space, and applied it to an image in image space. The integrated intensity of the 2D Fourier transform has been used to generate images from laser speckle[2]. But to take full advantage of the power of Fourier-based methods, it is important to have a method that separates noise from the characteristic spectrum of frequencies that uniquely identify the image.

Spectroscopy is a process of identifying characteristic points along a spectrum. A one-dimensional signal has one independent variable and one dependent variable, and its spectrum can be plotted as a function. Identifying important signal peaks can be done by inspection, which makes up the vast bulk of spectroscopic research. The two-dimensional (2D) signal of the Fourier spatial frequency of a 2D imaging plane has two independent variables, and one dependent variable. A central problem in understanding the data presented in the spatial frequency spectrum of a 2D image is how to make use of all the information, and to eliminate noise without losing information. Two methods are common: the first, picking a principal directional component, and presenting the one-dimensional spectrum along that axis[3], and the second, averaging over the whole, or a sub-region of the 2D fast Fourier Trasnform (FFT)[4]. The problem with these methods is that, although they allow for the expertise of the person making the analysis, they leave out a great deal of information that may not be immediately recognized as important.

An interactive visual tool to guide the user in identifying characteristic frequencies can help streamline the process. In addition to using analytical methods—the identification of peaks, for example—this tool also is designed to engage the human qualities of perception and recognition—such as visual harmony, subitization, and intuition.

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1.1 The Fourier Spatial Frequency Analyzer

We have developed the Fourier Spatial Frequency Analyzer (FSFA) to accomplish this task. An interactive tool, the FSFA is used to compare images for similarities and differences in Fourier space, and both allows for expert input, and offers a way to check for the efficacy of user choices. In this paper we present the basic features of the FSFA, and demonstrate how it might be used to advance Fourier-based image analysis. The user is presented with four panels in a 2 by 2 array. The top two panels contain, on the left, the 2D FFT of a time series of images of a single sample to be analyzed, and on the right, the inverse 2D Fast Fourier Transform (IFFT) of the left panel. The bottom two panels contain the same information for a second sample. The user interface is shown in Fig 1).

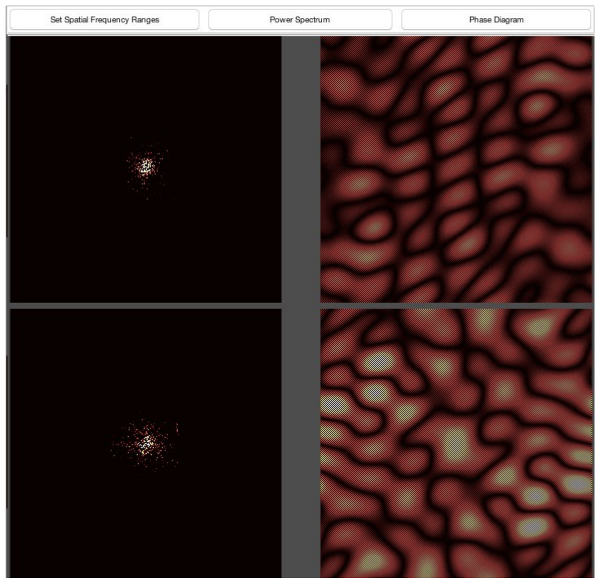

Figure 1. The user interface of the Fourier Spatial Frequency Analyzer. The top two panels show the 2D FFT and IFFT respectively of the first sample for analysis. The bottom two panels are for the second sample. The user can select frequencies to examine, and can choose to look at the IFFT in either the power spectrum or the phase map.

2. METHOD AND RESULTS

2.1 The Data Sample

Our data consists of 300 frames of a video of laser speckle from different suspensions of nanoparticles. The particles were reconstituted high density lipoprotein (HDL) which has a diameter of 10 nm, and is composed of phospholipid and protein. (Although native HDL carries cholesterol, for these experiments, we used cholesterol-free reconstituted HDL.) The suspension medium was prepared at 3 different concentrations of salt, 0, 300, and 600 mM. Delipidated HDL will begin to form rouleaux in 300 mM saline, and will aggregate further in 600 mM. The suspensions, therefore, represent samples of “the same” material, in different physical states. A circularly polarized laser was directed into the sample, and 300 frames captured within 5 s. at an angle of 45 degrees to the incident beam. The images are typical of laser speckle. A seemingly undifferentiated vision of noise fluctuating over time. Fig 2. shows typical images with very little difference between them visible to the eye.

2.2 Selection of Characteristic Frequencies

Fig. 3. shows the power spectrum of the 2D FSFT for the two images in Fig. 2. Although it is possible to select characteristic frequencies form the 2D FFT by thresholding, this tool offers the user a chance to make a choice based on visual appearance. In Fig. 2. a white circle has been drawn over the FFT at a distance of 48 pixels from the center of the image. This corresponds to the Fourier spatial frequency 48 cycles per unit image size (cpi). It can be seen that there are more contributing spatial frequencies above 48 cpi in the 600 mM preparation than in the 300 mM preparation. The FSFA allows the user to select an array of frequencies for inspection, either continuous or individually selected. As a first attempt at identifying characteristic frequencies, we can select all SF above 48 cpi.

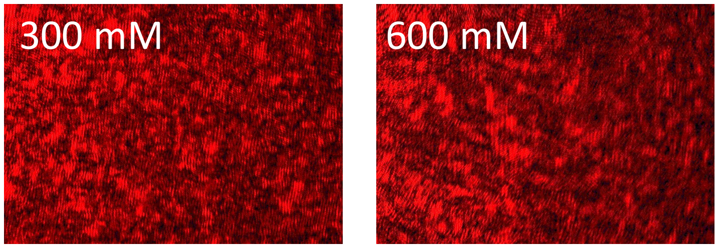

Figure 2) Single frames of a video capture of reconstituted HDL disks in 300mM saline (left) and 600 mM saline (right). Although the images appear to be “different” to our visual sense, a rigorous description of that difference is hard to formulate.

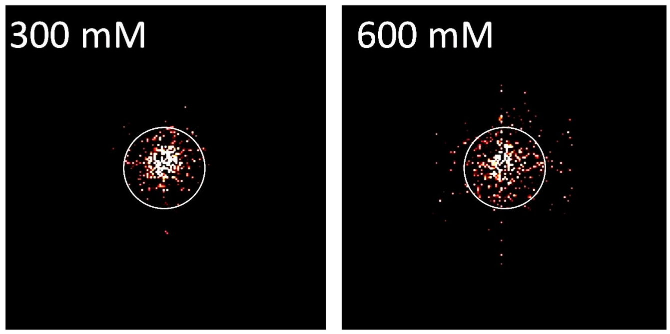

Figure 3. The 2D FFT of reconstituted HDL disks in 300mM saline (left) and 600 mM saline (right). The white circle is at the spatial frequency of 48 cpi. It can be seen that there are more high-frequency contributions to the 600 mM sample.

2.3 Characteristic Frequency Inspection

Following selection of our first-approximation characteristic SF, the FSFA presents the user with the inverse 2D FFT of the selected frequencies. This step allows an instantaneous appraisal of the choice made in the previous step. Fig. 4. shows the inverse 2D FFT of the FFT in Fig. 3, with selected frequencies only. It is immediately apparent that there is different information in the first panel than in the second. The lack of complicated patterns in the 300mM preparation indicates that spatial frequencies above 48 cycles per image contribute very little to the information in the image. Conversely, in the 600 mM preparation on the right, the honeycomb structures, and the cloudy shapes indicate a contribution from high frequencies. Also in Fig. 4., visual inspection shows a repeated sinusoidal motif of approximately 15 cycles per image in the horizontal direction, and about 4 cycles per image in the vertical direction. It should be noted that these motifs are not from the IFFT of SF 4 cpi and 15 cpi, but rather from higher harmonics of the lower frequency. These patterns are indicative of a harmonic frequency of greater intensity at lower frequencies that underlies the visual pattern, and gives a clue about where to look for additional characteristic frequencies. Selecting for these lower harmonics gives the IFFT shown in Fig. 5.

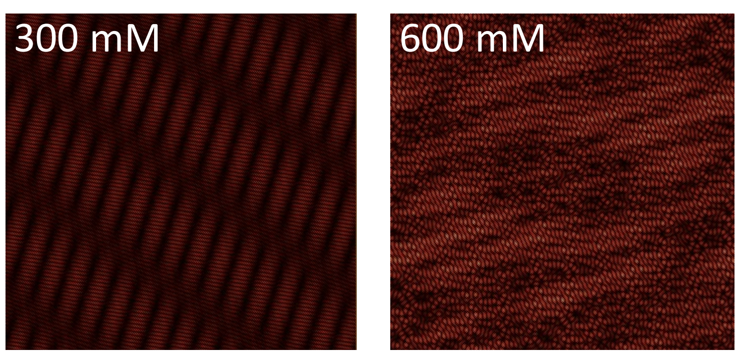

Figure 4. The inverse Fourier transform of the 2D FFT in Fig 3. Note the characteristic pattern in the 600 mM sample, vs. the sinusoidal motif of the 300 mM sample.

2.4 Differentiation of signals

The images in Fig. 5. are in sharp contrast to the original images in Fig. 2., and can be clearly distinguished from each other in a number of ways that can be easily described by such terms as granularity and roughness. Having selected characteristic frequencies using the FSFA, the user can now pursue quantitative procedures such as integrated intensity, time-decorrelation, and intensity moment analysis for use in further analysis.

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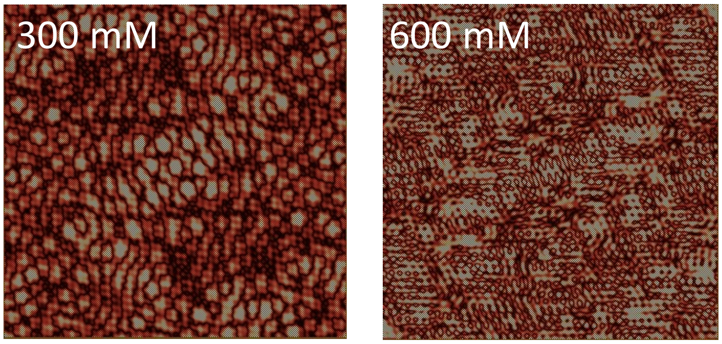

Figure 5. The 2D IFFT of the FFT in Fig. 3, with selected frequencies 4 cpi, 15 cpi, and 48 cpi t0 50 cpi..

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