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Monitoring foam coarsening using a computer optical mouse as a dynamic laser speckle measurement sensor

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Abstract. In this paper, we present an experimental approach to track coarsening process of foam using a computer optical mouse as a dynamic laser speckle measurement sensor. The dynamics of foam coarsening and rearrangement events cause changes in the intensity of laser speckle backscattered from the foam. A strong negative correlation between the average speed of the cursor and the evolution of bubble diameter was found. We used microscopic images to demonstrate that decrease in speed is related to increase in bubble size. The proposed set-up is not very expensive, is highly portable and can be used in laboratory measurements of dynamics in other kinds of opaque materials.

Keywords. Aqueous foam; optical flow sensor; dynamic laser speckle; computer optical mouse.

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1. Introduction

Aqueous foams are colloidal systems with high concentration of gas bubbles in a liquid matrix. These systems are subjected to spontaneous changes due to drainage and coarsening. Drainage is the flow of liquid through channels and nodes between bubbles. The coarsening is related to the increase of the volume of some bubbles at the expense of others. This can be explained by two mechanisms. One is coalescence (in this case, two bubbles approach and merge into a larger one). The other mechanism is due to gradients of pressure, within and outside the bubble, driving the gas from smaller bubbles to bigger bubbles [1,2]. Naturally, a complete description of foam dynamic properties requires a rheological study; it deals with rearrangement induced by applying a shear stress or vibrations [3]. The wet foams have generated great scientific interest because of their commercial and industrial uses; their more recent and important applications are in food, cosmetics, security, constructions, etc. In the last two decades, several experimental techniques and theoretical models have been proposed for exploring the properties and complex behaviour of the foams. However, some physicochemical aspects of foam remain unclear, which motivate new procedures to understand the dynamics of foams [3,4].

The diffusing wave spectroscopy (DWS) technique is the most commonly used technique to study the dynamics of foam. It is an optical and non-invasive probe extensively used for measuring the dynamics of light scattering media. It relates the decay time of intensity autocorrelation function of speckle pattern with the information on the sample dynamics. This technique is suitable for opaque and turbid materials and it is based on the random walk of photons inside the material [5,6]. Some DWS-inspired procedures include speckle visible spectroscopy (SVS), relating the dynamics with variance of intensity of speckle pattern [7,8] and time-resolved correlation (TRC). In TRC, a charge-coupled device (CCD) camera records the image of multiple speckles from the light transmitted or backscattered by the sample; the correlation degree between pairs of images taken at a given lag is measured, and averaged over each pixel, as a function of the time at which the first image was taken [9]. Although Raman scattering is not a tool frequently used to study liquid foam, an empirical model to explain the coupling between drainage and coarsening has been proposed [10].

In this paper we show that the optical flow caused by the temporal evolution of speckle pattern, induced by the dynamics of foam can be monitored via the computer optical mouse. Recent applications of the optical mouse, particularly as a sensor of dynamic speckle or time-varying speckle, realize the possibility of studying the dynamics of foam using these types of sensors [11–18].

2. Experimental set-up

Often, for basic research on foam, commercial brands are used because of their high reproducibility and low absorption of light. In this experiment, we used the shaving cream, Gillette Foamy (Mentol), consisting essentially of an aqueous solution of mixed ionic surfactants or foaming agents (triethanolamine, palmitic acid, sodium lauryl sulphate and stearic acid), saturated with hydrocarbon gases (butane, isobutene and propane) [5,6]. Other ingredients are: menthol, alcohols and fragrances. Once these contents are released, the gases come out of the solution, the surfactants adsorb on bubble interfaces, and foam is formed.

The sample of the foam was sandwiched between the glass microscope slides ($26 \times 76 \times 1.2$ mm), which were separated by 1 cm. Then, the sample was placed over the hole of an integrating sphere (Ocean Optics ISP-REF, integrating sphere). This hole permits uniformly illuminating a circle of 1 cm diameter of the foam. During the experiment no flow of foam was appreciated on the open sides of sample cell (a cuvette is strongly recommended). Although normally short wavelengths in the visible region are used, we used light from the He–Ne laser (wavelength 632.8 nm and power output <10 mW), guided via the optical fibre (P400 UV–VIS, Ocean Optics) to the integrating sphere, in order to illuminate the foam (see figure 1). Integrating sphere assures a diffuse illumination on the sample.

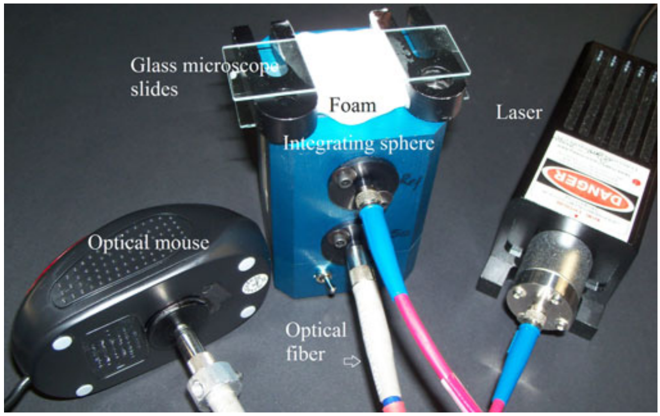

Figure 1. Experimental setup.

Backscattered light, laser speckle, from the lower section of the shaving foam is collected and guided by a multimode optical fibre to an optical mouse eSenses (resolution 0.0318 mm, 800 dpi) coupled with a SMA 905 connector. The light emitting diode (LED) of the optical mouse was blocked using a dark adhesive tape. Working principle of the

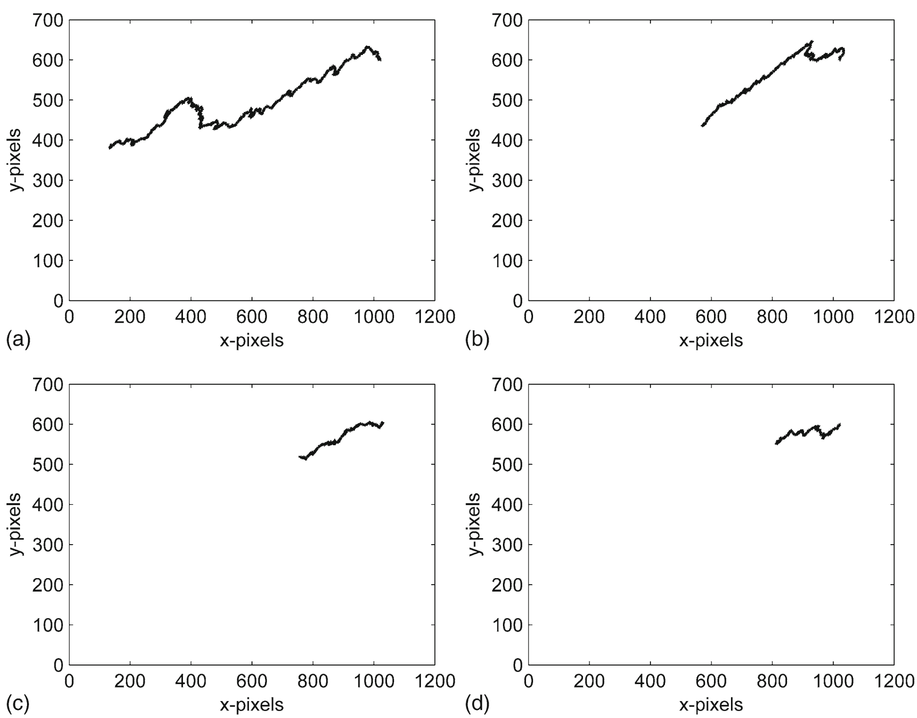

Figure 2. Path of the cursor at (**a**) 33 s, (**b**)–(**d**) 15, 45 and 60 min later respectively.

optical mouse is given in [11,19]. Essentially, using a complementary metal–oxide–semiconductor (CMOS) camera, the mouse correlates images of the dynamic speckle, refreshed to ∼0.73 ms/sample. The position of the maximum of the correlation output indicates the displacement of the cursor on the screen of the computer. Alternatively, the speckle signal can be acquired from the CMOS directly.

Fluctuations in the speckle pattern, sensed by the mouse, cause the cursor to move in the computer screen. This motion is featured using the following three variables: The sampling time and two spatial coordinates, x_i, y_i, sampled at time, t_i [20]. For the nth dataset, the average speed of the cursor can be calculated using eq. (1),

$$\upsilon_n = \frac{1}{\Delta t} \sum_{i=1}^{N} \sqrt{(x_{i+1} - x_i)^2 + (y_{i+1} - y_i)^2}, \tag{1}$$

where x_{i+1}, y_{i+1} are the spatial coordinates at time t_{i+1}. That is, adding the magnitude of N displacements, corresponding to two consecutive cursor positions, gives the total distance travelled by the cursor when $\Delta t = 30$ s.

In our experimental protocol, data acquisition started 33 s after the sample was sprayed out of the shaving cream can. A script written in Matlab® allowed the datasets scanning the cursor position for 30 s. Delay between scan was established in 1 min. Before each scan, the cursor was located at the same start point of coordinates (x, y) on the computer screen, in this case (1024, 600). Selecting this position ensures that the cursor does not

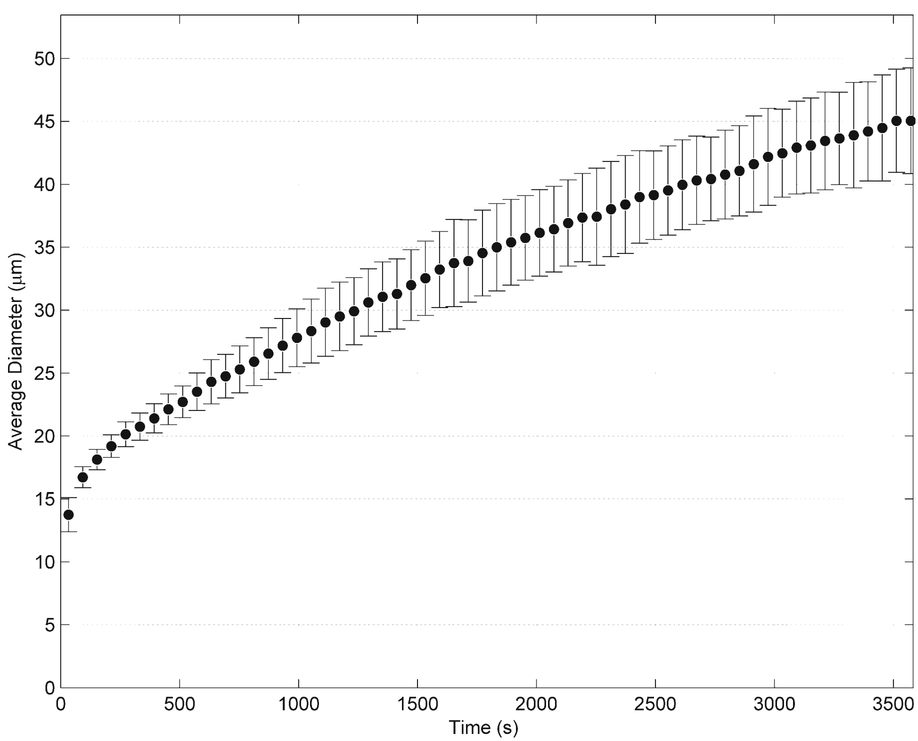

Figure 3. Average bubble diameter against time in 1 h.

reach the edge of the screen, which affects the sampling coordinates. The process is repeated for ∼1 h, completing 60 datasets. Each set of data is saved to a file for later processing.

3. Results and discussion

Figure 2 shows the path of the cursor at time 33 s (figure 2a) and 15, 45 and 60 min later (figures 2b–2d) respectively. Notice that, the total distance travelled by the cursor, during 30 s, decreases with time. In addition, cursor movement is predominantly at the same direction, which means that the change of optical flow also changes in one direction.

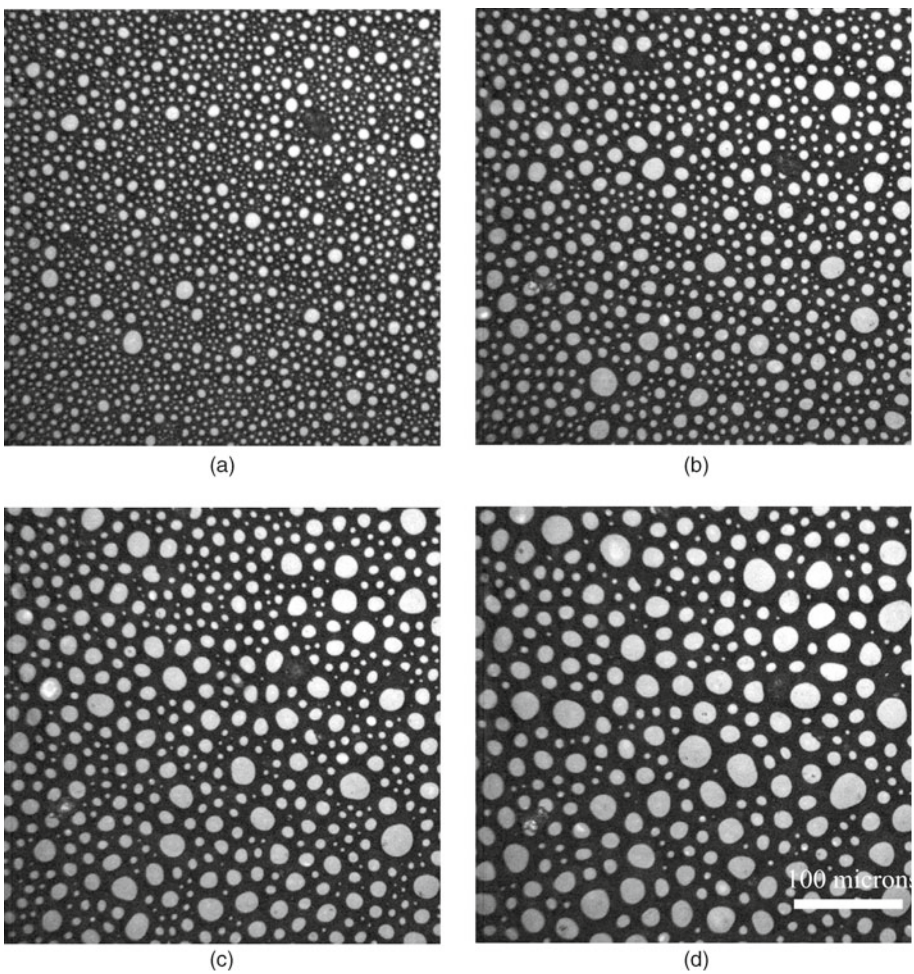

Figure 4. Optical microscope images of shaving cream foam at respective times mentioned in figure 2.

On the other hand, in figure 3, we show an increase in the mean bubble diameter in 1 h. Initially, the average bubble diameter was 14 μm, and with coarsening the size increased to 45 μm. The standard deviation will be larger (symmetric error bars of unit standard deviation) when foam ages, that means, the diameter distribution is more uniform at the early time of foam life. This behaviour is corroborated using optical microscope images (bubble against glass slide) taken at the same times considered above (see figure 4), and in agreement with previous reports on the growth tendency for the coarsening of foam bubbles, assuming a two-dimensional system [5,21].

Bubble size was measured using routines from the image processing toolbox of Matlab®. In order to achieve accurate results in the statistics calculation, the optical microscope images of the foam were preprocessed: correcting the background illumination and converting the image into a binary image. Using pixel connectivity appropriated procedures the bubbles were labelled in a region of interest of 512 $\times$ 512 pixels. Assuming bubble-like discs, the area and then its respective diameter were calculated.

It would be reasonable to relate this behaviour of the optical flow, sensed by the mouse, with the change-temporal rate of the cross-sectional area of the bubbles, near the surface of the glass slide. In figure 5, average speed (in pixels/s) vs. time is plotted. It is evident from the figure that the average speed decreases with time. The standard deviation is larger in the first few seconds of data acquisition (symmetric error bars of unit standard

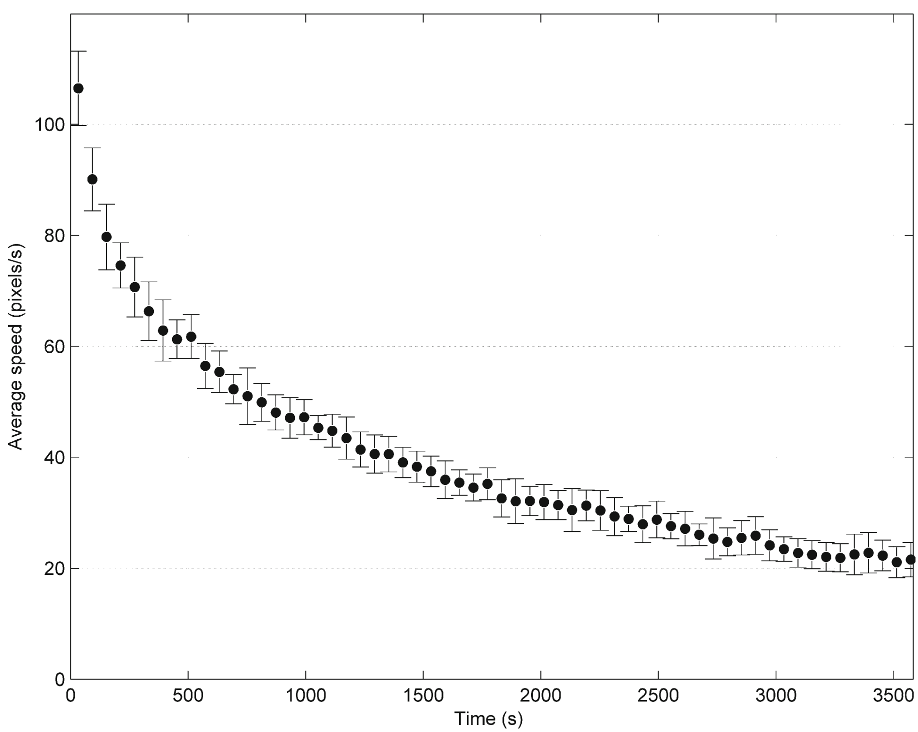

Figure 5. Average speed of the cursor against time.

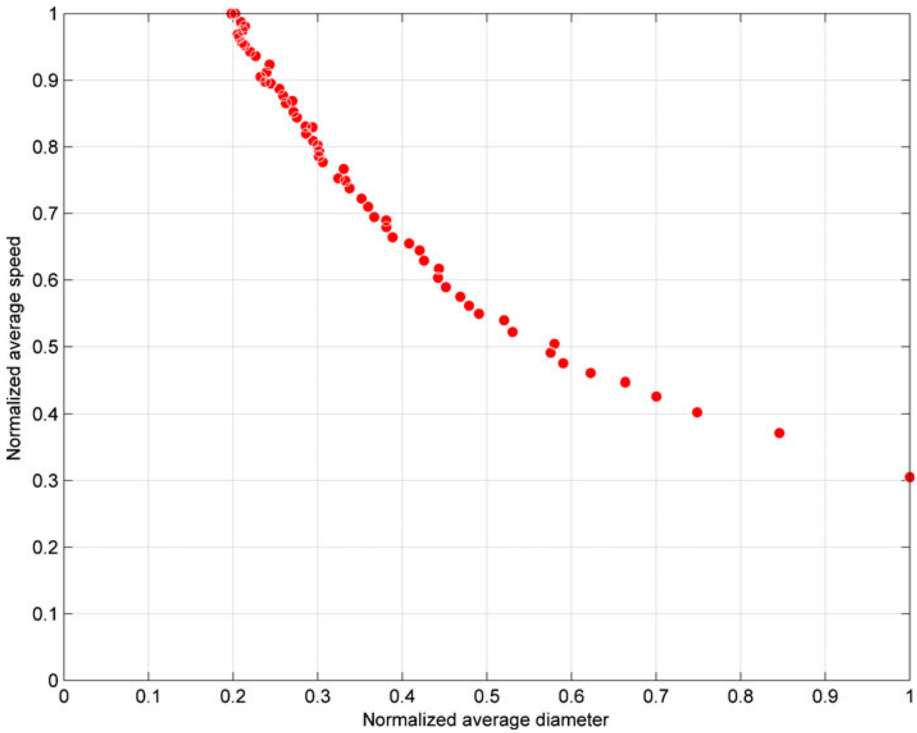

Figure 6. Normalized average speed of the cursor vs. normalized mean bubble diameter.

deviation). It is certainly related to the initial condition during the measurements and the uncertainty caused by the faster motion (at this time) of the dispersing medium.

Figures 3 and 5 suggest a relationship between the mean diameter of the bubbles and average speed of the cursor through foam ageing. The correlation coefficient between these variables, previously normalized to its respective maximum, is -0.96. This strong negative correlation is manifest in figure 6, in which normalized average speed of the cursor against normalized average bubble diameter is plotted. That is, high values of average speed of the cursor are related to the small diameters of the bubbles, which appear in the foam in the beginning. Although, as mentioned above, dynamics of the foam is a complex process, this result shows that it is possible to relate the growth, and perhaps rearrangements events, of the bubbles with changes in the optical flow, sensed with the optical computer mouse, produced by dynamic laser speckle.

4. Conclusions

We have exposed the potential of dynamic laser speckle and a computer optical mouse to track the changes in the speckle pattern of laser light multiply scattered from aqueous foam. This procedure can be used as an alternative to the more sophisticated DWS. Although it is necessary to consider the effect of different wavelengths, the type of foam, thickness of the layer of foam between glass microscope slides, the results obtained describing dynamical of foam (shaving cream foam) are in agreement with other previously reported results using DWS-inspired procedures such as speckle visible spectroscopy, relating the dynamics with variance of intensity of the speckle pattern and time-resolved correlation (TRC). Finally, dynamic laser speckle and a computer optical mouse can be used to study a wide range of dynamic processes, which until now have been studied using traditional dynamic light scattering techniques. However, the contributions of different mechanisms in the coarsening and rearrangement in the foam are not yet evident.

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