Environmental Noise Impact on Dynamic Speckle Imaging

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Abstract: Environmental noise impact on dynamic speckle visualization of speed of changes in 3D objects with outdoor image capture is estimated. Efficiency of analysis is proved by processing synthetic and experimental data, including also compressed images.

1. Introduction

Dynamic speckle imaging (DSI) exploits high sensitivity of speckle to micro-changes of topography or the refractive index to visualize speed of processes in 3D objects [1-3]. A 2D map of a statistical parameter is built as a speed measure from a sequence of time-correlated speckle images. The built activity map comprises strongly fluctuating entries but succeeds to show areas of faster or slower changes on the object surface. Nondestructive testing of industrial or biological objects entails data acquisition in outdoor conditions leading to inevitable increase of the phase noise level due to lack of vibration insulated environment. We studied in this work the noise impact on the DSI sensitivity by modelling external noise as time-correlated phase added to the complex amplitude of the light field on the object surface and proved outdoor efficiency of the DSI by conducting a polymer drying experiment. Analysis was done also for compressed speckle images, which are needed for monitoring of processes.

2. DSI efficiency in the presence of environmental noise

In DSI, a linearly polarized laser light illuminates the object and a camera controlled by computer records speckle images (Fig.1) which encode variation of intensity due to the phase changes in the complex amplitude of the diffusely reflected light. At vibration insulation, no environmental phase noise goes to the phase change induced by the studied process into the light field, which arrives at the camera objective. At outdoor measurement, such a phase noise may decrease the activity map contrast. To check its impact, we generated at wavelength 532 nm synthetic speckle patterns of size 256×256 pixels with practically symmetric intensity distribution at uniform illumination by producing correlated in time wrapped phase distributions on the object surface. They were further propagated to the camera aperture through the objective lens. Generation started with a 2D array of random delta-correlated phase values uniformly distributed from 0 to 2π. The phase change in time was normally distributed. Activity at object point (x, y) was given by the temporal correlation radius, $\tau_c(x, y)$, of the normalized temporal correlation function $\rho(\tau) = \exp(-\tau/\tau_c)$ of intensity fluctuations. The standard deviation of the phase change between successive images separated by interval Δt was $\sigma_\varphi = N(0,1)\sqrt{\Delta t/\tau_c(x, y)}$. The environmental phase noise with a temporal correlation radius, τ_{noise}, has standard deviation, $\sigma_{noise} = N(0,\alpha)\sqrt{\Delta t/\tau_{noise}(x, y)}$. Integration of speckle by the camera pixels was also modeled. The test object consisted of a background with $\tau_{cb} = 100\Delta t$ and higher activity areas as the letters DH and 3 circles with $\tau_c = 10\Delta t$. We built maps of the modified structure function (MSF) $S(i,k,m) = N^{-1}\sum_{l=1}^{N}\left|I_{ik,l} - I_{ik,l+m}\right|$ at time lag, $\tau = 10\Delta t$, from N = 256 images, where $I_{ik,l}$ is the intensity at pixel (i, k) at instant $l\Delta t$. The MSF maps at increasing α for $\tau_{noise} = 0$ are shown in Fig.1 (a-d). The letters and the circles are clearly seen even at rather strong perturbation (α = 0.3) despite the low map contrast. The higher activity areas are detectable due to lack of correlation between the noise and the observed process. At α = 0.5, the process is entirely buried in noise. We characterized the map quality by the sensitivity parameter, $\beta = \left(\bar{S}_h - \bar{S}_l\right)/\bar{S}_h$, where $\bar{S}_{h,l}$ are the mean MSF values in the higher activity area and the background. The parameter β is shown in Fig.1 (e,f) for increasing τ_{noise} for $\tau_{cb} = 100\Delta t$ (e) and $50\Delta t$ (f). The delta-correlated noise impact is most substantial. At increasing τ_{noise} from 0 to 200 Δt, parameter β approaches its value at α = 0. For this reason, we focused on the case $\tau_{noise} = 0$ and checked the noise impact for different formats of the acquired data: 8-bit and 4-bit encoded bitmap images [2], binary images [1] and JPEG compression [3]. We used a mean intensity in time, $\bar{I}_{ik}$, as a threshold for each pixel to form sequences consisting of $\vartheta_{ik,l} = \mp 1, l = 1..N$ depending on $I_{ik,l}$ being smaller or larger than $\bar{I}_{ik}$. Then we found the polar correlation function (PCF) $P(i,k,m) = N^{-1}\sum_{l=1}^{N-m} \vartheta_{ik,l}\vartheta_{ik,l+m}$, which gets a lower value at higher activity. The sensitivity parameter for the compressed data is shown in Fig.1 (g) as a function of α. We see that the DSI sensitivity is acceptable for rather high noise levels.

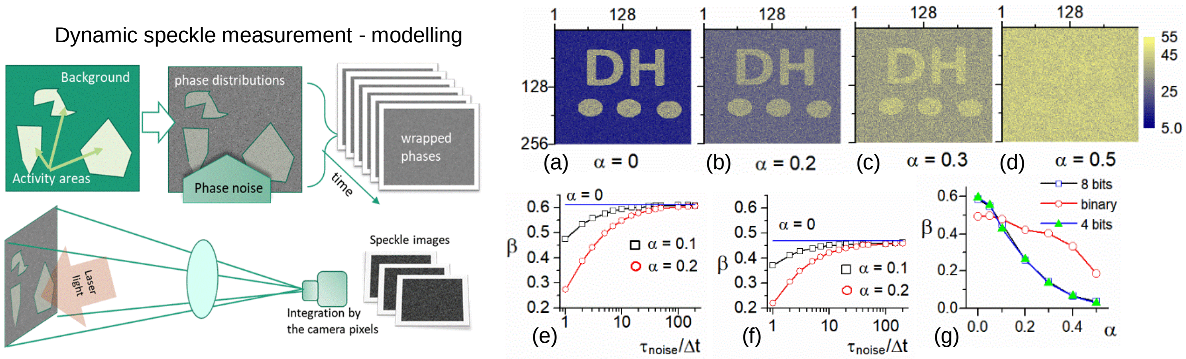

Fig. 1. Simulation of dynamic speckle measurement in the presence of environmental noise; (a,b,c.d) – MSF activity maps for delta-correlated in time noise, (e,f) – sensitivity parameter as a function of τ_{noise} for $\tau_{cb} = 100\Delta t$ (e) and $50\Delta t$ (f); (g) - sensitivity parameter as a function of α at $\tau_{cb} = 100\Delta t$.

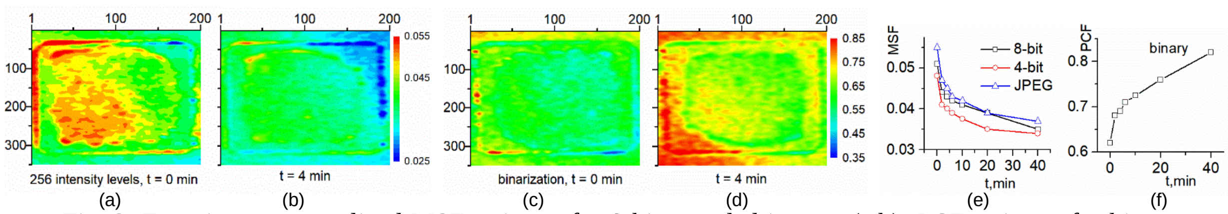

Fig. 2. Experiment: normalized MSF estimate for 8-bit encoded images (a,b); PCF estimate for binary images (c,d); average value of activity estimate as a function of the time offset for different types of compression (e,f); $\tau = 10\Delta t, N = 256$, wavelength 532 nm.

For the experiment, we dissolved 40 mg of a commercially available azopolymer in 400 µL of water. A 100 µl droplet was spread on a glass substrate. Slightly non-uniform illumination entailed using the normalized MSF algorithm. Several sets of 256 speckle patterns were recorded at the time offsets t = 0, 2, 4, 6, 10, 20 and 40 min from the start of the experiment. The optical set-up was positioned on an optical table without active vibro-insulation. The activity maps computed at τ = 10Δt from 8-bit encoded patterns and from binary patterns are shown in Fig.2 for two time offsets. Average value of the activity estimate as a function of the time offset is also shown for different types of compression. Despite the environmental phase noise, decrease of activity due to the drying process is correctly detected. This noise is evidenced by the presence of activity at large time offsets. Activity within the droplet is slightly higher in its central part than in its periphery at the beginning of the drying. At larger offsets, it becomes more or less uniform. Comparison of the average activity for the ground truth map calculated from 8-bit encoded patterns to the values for maps from the compressed data confirm applicability of compression.

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3. References

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