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Digital speckle correlation method used to measure blood flow velocity

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The digital speckle correlation method (DSCM) used to measure blood flow velocity is here analyzed. The experiment is designed to obtain the dynamic speckle pattern of blood which is shot by CCD. Then the DSCM is used to process the sequential images and the experiment is simulated. The experimental results show that the DSCM can measure blood flow velocity, and have a good agreement with the simulation results.

Keywords: images, blood velocity, digital speckle, correlation function.

1. Introduction

Blood flow velocity measurements have great clinical significance. By the 1980s, the blood flow velocity could be measured by a laser Doppler microscope [1–3]. The principle is: a laser beam is focused onto a capillary by means of a lens, mirror and beam splitter system and the measurement of blood cells velocity in a direction substantially perpendicular to the surface of the tissue is effected by detecting directly back-scattered radiation. Besides, the holographic technology was also used to investigate biological objects [4]. In recent years, the new technologies of blood flow measurement have developed, such as: the fluorescein isothiocyanate (FITC) fluorescence labeling technology, the microvascular imaging technology [5]. But the above-mentioned methods have some limitations, for instance: laser Doppler method must use the optical heterodyne technology and it is only an indirect measurement. In addition, the procedure is complex and the equipment – expensive.

Recently, the digital speckle correlation method (DSCM) [6–9] has shown its special merits in deformation measurement of materials and structures [10], namely being non-contact, making use of a simple optical setup, needing neither special preparation nor special requirement for the test environment, showing no sensitivity to illumination nor vibration [11]. When the blood was illuminated by light, the speckle was be formed. Thus the experiment designed to measure the blood instant velocity has been presented in this paper.

2. Theory

2.1. The correlation function of speckle pattern

Assuming that a diffuser surface moves with the speed v. Figure 1 shows the beam path and coordinate direction. The diffuser screen is a pure phase object and is illuminated by coherent light. The complex amplitude of speckle pattern $A(r, t)$ can be written as:

$$A(r, t) = \int_{-\infty}^{\infty} p(r_0) A_0(r_0, t) h(r, r_0) \, \mathrm{d}r_0 \tag{1}$$

where $p(r_0)$ is the aperture function, $h(r, r_0)$ is the weight function for describing the transmission of optical field, and $A_0(r_0, t)$ is the emergent amplitude of the light source. The dynamic speckle intensity can be expressed as follows:

$$I(r, t) = A(r, t) A^*(r, t) \tag{2}$$

The fluctuation of dynamic speckle intensity $\Delta I(r, t)$ is given by

$$\Delta I(r, t) = I(r, t) - \langle I(r, t) \rangle \tag{3}$$

where $\langle I(r, t) \rangle$ is the average intensity of the speckle. It is well known that the space-time across correlation is written as [7]:

$$R_{\Delta L}(r_1, r_2, t_1, t_2) = \langle \Delta I(r_1, t_1) \Delta I(r_2, t_2) \rangle \tag{4}$$

Since $A(r_1, t_1)$ and $A(r_2, t_2)$ are the joint circular symmetric complex random variables, from the principle of Gaussian square we can get:

$$R_{\Delta L}(r_1, r_2, t_1, t_2) = \left| A(r_1, t_1) A^*(r_2, t_2) \right|^2 \tag{5}$$

Using the Gauss beam, whose girdling radius is ω_0, to illuminate the diffuser screen, and defining the axial line of the beam as being the Z-axis, which is parallel to normal of the diffuser surface average plane, the aperture function can be written as:

$$p(r_0) = \frac{\omega_0}{\omega(z_0)} \exp\left[\frac{j 2\pi z_0}{\lambda}\right] \exp\left[\frac{-|r_0|^2}{\omega^2(z_0)}\right] \exp\left[\frac{j \pi |r_0|^2}{\lambda \rho(z_0)}\right] \tag{6}$$

where z_0 is the distance from the girdling plane to the diffuser screen; $\omega(z_0)$ is the effective radius of the illumination spot on the emergent plane of the diffuser screen; $\rho(z_0)$ is the curvature radius of the optical wave front focused onto the emergent

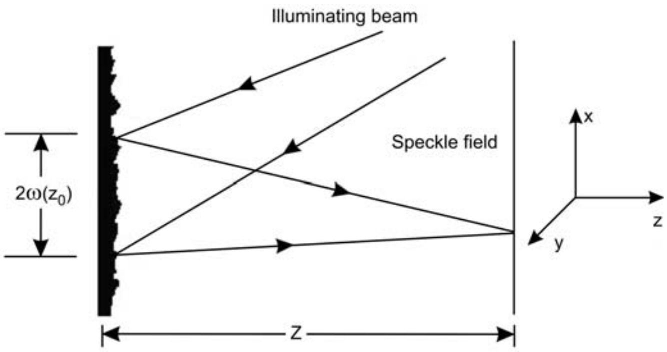

Fig. 1. Beam path and coordinates.

plane of the diffuser screen. As we know, the power function corresponding to Fresnel diffraction is:

$$h(r, r_0) = \frac{1}{j\lambda z}\exp\left[\frac{j2\pi z}{\lambda}\right]\exp\left[\frac{j\pi|r-r_0|^2}{\lambda z}\right] \tag{7}$$

Substituting Eq. (6) and Eq. (7) into Eq. (1), and then substituting Eq. (1) into Eq. (5), after normalization, we can obtain:

$$r_{\Delta I}(\Delta r, \tau) = \frac{R_{\Delta I}(\Delta r, \tau)}{R_{\Delta I}(0, 0)} = \exp\left[-\frac{|v|^2\tau}{\omega^2(z_0)}\right]\exp\left[-\frac{\pi^2\omega^2(z_0)|\sigma v\tau - \Delta r|^2}{\lambda^2 z^2}\right] \tag{8}$$

When $\tau = 0$, the normalized space-time correlation function can be obtained:

$$r_{\Delta I}(\Delta r, 0) = \exp\left[-\frac{\pi^2\omega^2(z_0)}{\lambda^2 z^2}|\Delta r|^2\right] \tag{9}$$

$\omega(z_0)$ and z are the invariables for the identical optical system. Then, the relational expression of $r_{\Delta I}$ and Δr can be gotten from the space-time correlation function (Δr is the size of the move distance, but the move direction cannot be determined). How to judge the move direction will be described as follows.

2.2. Serial dynamic speckle and direction determined

Since the distribution of the speckle is random, the statistic characteristic is different for the area around every dot. In the following part of this paper, the area will be called the sub-image of the dot. It usually has $n \times n$ pixels. If the diffuser screen has micro-displacement in a plane, it can be considered that the micro-displacement only alters the locus of scattering sub-set, not affecting scattering characteristic. So the sub-image of the dot on the speckle pattern corresponds to the displacement of the dot. When the dot k moves to the dot k' on the object plane, the sub-image A of the dot k correspondingly moves to the sub-image A' of the dot k' in the speckle pattern, and the two sub-images and their correlation coefficient should be maximal. Therefore, the position of the dot k' can be determined by correlation calculation hunting for a sub-image. The process is as follows: a series of sub-images are shot at different positions on the speckle pattern after move. They have the same pixels with the sub-image A, and for each of them the correlation coefficient with the sub--image A is calculated. The closer the dot k', the larger the correlation coefficient. When the correlation coefficient gets to the maximum, the center of the sub-image is at the position of the dot k'. It is the principle of the speckle correlation. For obtaining the continuous speckle, CCD is controlled to shoot images at a set interval while the object is moving. The collection frequency of the CCD is n frames per second. Assuming that a series of speckle patterns are captured and denominated u_1 to u_m, we call them serial dynamic speckle patterns. Firstly, taking speckle patterns u_1 and u_2 into consideration, the sub-image A_1 of the measuring dot $k_1(x_1, y_1)$ is selected on the speckle pattern before move. The sub-image of the dot $k_2(x_2, y_2)$, to which the dot $k_1(x_1, y_1)$ moves, can be found by means of speckle correlation calculation (maximal correlation coefficient), and the move distance Δr and the move direction $\tan\alpha$ can be expressed by pixel differences:

$$\Delta r = \sqrt{\Delta x_1^2 + \Delta y_1^2} \qquad (\Delta x_1 = x_2 - x_1,\ \Delta y_1 = y_2 - y_1) \tag{10}$$

$$\tan\alpha = \frac{\Delta y_1}{\Delta x_1} = \frac{y_2 - y_1}{x_2 - x_1} \tag{11}$$

From the displacement, the velocity can be gotten:

$$v = n\Delta r \tag{12}$$

Secondly, taking speckle patterns u_2 and u_3 into consideration, the new measuring dot A_2 is selected in the speckle pattern u_2, and the dot A_3, to which A_3 moves, can be found by means of DSCM. The rest may be deduced by analogy. So the displacement can be continuously measured and the successive tracing and velocity can be obtained.

3. Experiment results and analysis

3.1. Setup of experiment

Figure 2 shows the setup of the experiment. A fresh muscle of the rabbit leg with the microvascular, lymph tissue is laid on a stage and the stage is fixed on a numeric control caterpillar track which can control the velocity and direction of the stage. A semiconductor laser (650 nm) is used to illuminate the muscle through an extender

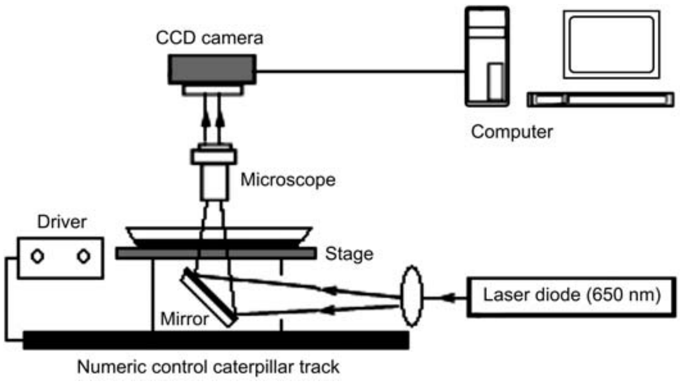

Fig. 2. Setup of experiment.

lens and reflecting mirror; A microscope is located in between the CCD and mirror, and the image of blood in the microvascular was shot by a 1024×768 pixels CCD. In this experiment, the velocity of a caterpillar track is taken instead of the velocity of blood flow. When the track is moving, the velocity of the caterpillar track and the velocity of blood flow are identical. Then, serial images of the speckle pattern are shot. The collection frequency of the CCD is 500 frames per second, the enlargement factor of CCD lens is 10. The images are stored into the PC through an image board.

3.2. Computer simulation tests – experiment results and discussion

3.2.1. Computer simulation tests

A program is fabricated to simulate the experiment and is applied to test the efficiency of the DSCM. In the software simulation model, one BMP image of the real speckle pattern of a laser diode (LD) at wavelength $\lambda = 650$ nm is used. The image is shot by the same CCD in Fig. 2 and is stored in PC for test. Assuming that the image moves in a track following the curve $y = x^2$ ($x \in [0, 10]$), the move trace can be obtained by means of the DSCM. At the same time, the image is collected when the aluminum plate is moving following the curve $y = x^2$ ($x \in [0, 10]$), Fig. 3 shows both the

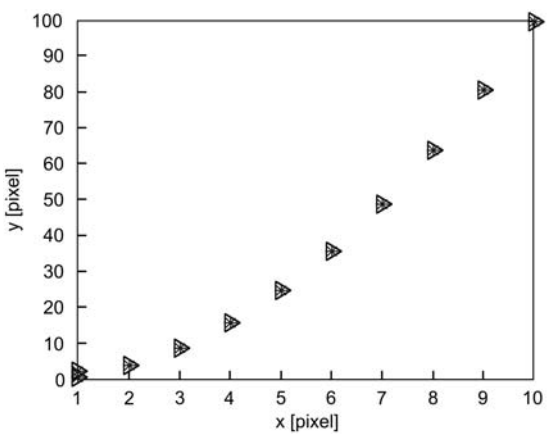

Fig. 3. Theory and experimental measurement curve of $y = x^2$ ($x \in [0, 10]$).

simulation ($*$) and the experimental ($\triangleright$) track. We can see from Fig. 3 that simulation and experimental track are concurrent. Only at the point (1, 1), the displacement is too small, which is the cause of the error in the correlation coefficient. It shows that the theory of the DSCM is feasible.

3.2.2. Experiment results and discussion

Another program is designed for processing data. It can read-in the images and output the results. There are four output parameters: (x_i, y_i), v and α that represent the position and moving direction of the object. Initial (x_i, y_i) is (0, 0). $(\Delta x_i, \Delta y_i)$ represents pixel difference in coordinates of two adjacent images. α is the angle specifying the direction of the object's motion relative to the x-axis: $\alpha \in [0°, 90°]$ (Eq. (11)). Varying the speed of the aluminum plate, variant values of $(\Delta x_i, \Delta y_i)$ were obtained and varying the direction of the numeric control caterpillar track, variant values of α were obtained. $v = \Delta r/t$, where $\Delta r = (\Delta x^2 + \Delta y^2)^{1/2}$, t is the interval of the two adjacent images. The program outputs are α, $(\Delta x_i, \Delta y_i)$, $\Delta r/v$ and the error ε, calculated by $\varepsilon = \alpha - \alpha_0$.

The caterpillar track with the muscle was moving with varying direction and the same speed v = 10 mm/min. Some results of the experiment are shown in Tab. 1.

T a b l e. 1. Some results of experiment for v = 10 cm/s.

α_0 [deg]	α [deg]	ε [deg]
0.00	0.00	0.00
90.00	90.00	0.00
45.00	45.00	0.00
63.43	63.43	0.00
26.57	26.57	0.00
45.00	45.00	0.00
71.57	71.57	0.00
18.43	18.43	0.00
53.13	56.31	–3.18
36.87	33.69	3.18
78.69	75.96	2.73
11.31	14.04	–2.73

T a b l e. 2. Some results of experiment for fixedness sampling rate.

v [cm/s]	$(\Delta x, \Delta y)$ [pixel]	Δr [pixel]	$\Delta r/v$
8	(8, 8)	11	1.375
9	(8, 9)	12	1.333
10	(9, 10)	13	1.300
11	(11, 11)	15	1.364
12	(11, 12)	16	1.333

From Table 1 we can see that the deviation from the real angle is less than 3.18°, which is acceptable for blood flow velocity. Furthermore, the muscle was moving with varying speed and the same direction (Tab. 2). As shown in Table 2, the average measurement displacement Δr_{avg}, where $\Delta r = (\Delta x^2 + \Delta y^2)^{1/2}$, the measurement displacement and the speed of muscle have a good correspondence. Under these experimental conditions, the results prove the efficiency of the DSCM.

4. Conclusions

The usage of the DSCM to measure the blood flow velocity has been demonstrated. The application of DSCM is expanded and a practical method is presented for the blood flow velocity measurement. The blood flow velocity can be accurately confirmed by the DSCM. The experimental results are in good agreement with theory analysis and simulation. The experimental results and experimental operation prove that the method is simple and low-cost.

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