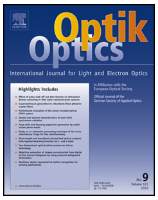
Optik xxx (2014) xxx–xxx

Contents lists available at ScienceDirect

Optik

journal homepage: www.elsevier.de/ijleo



Velocity measurement for moving surfaces using spatial filtering method based on area image sensor

Xin He*, Xiaoming Nie, Jian Zhou, Xingwu Long

National University of Defense Technology, College of Optoelectronic Science and Engineering, Department of Optoelectronics Engineering, Changsha 410073, China

ARTICLE INFO

Article history:
Received 2 December 2013
Accepted 10 July 2014
Available online xxx

Keywords:
Optical system
Velocity measurement
Differential spatial filter
Area CCD
Inertial navigation system

ABSTRACT

The idea of using spatial filtering method to measure velocity of vehicles for an inertial navigation system is put forward. Corresponding optical system, including a 532 nm solid-state laser as active illumination, is established. A 17.92 mm × 14.34 mm area charge coupled device (CCD) is employed both as detector and as spatial filter. The spatial filtering characteristics are theoretically analyzed using a power spectral density function. The spatial filtering operation of CCD is performed fully by software. Therefore, the parameters of the spatial filter, such as the size and the number of spatial period, are changeable. In addition, the CCD is arranged as two differential spatial filters without any other additional elements. Experiments are carried out to examine the feasibility of CCD as two differential spatial filters and the influence of the number of spatial period on the signal frequency. The results indicate that the more number of spatial period the more accurate measurements can be obtained, and show that the relation between signal frequency and velocity has good linearity. So this velocimeter is suitable to provide velocity information for a vehicle self-contained inertial navigation system.

1. Introduction

The velocity measurement using light has the important advantage that velocity can be obtained without disturbing the object. With the fast development of optoelectronic technology, many kinds of optical methods for velocity measurement have been proposed. Among all these methods, three of them have been paid more attention to than others, laser Doppler method [1–3], laser speckle method [4] and spatial filtering method [5–7]. Though the spatial filtering method has been received less attention than the other two methods, it has been applied to many aspects because of its simplicity and stability of the optical and mechanical system and a choice of light source since it was proposed in about 1960s [8]. Yoshihisa et al. used a transmission grating as the spatial filter for measurements of the flow velocity distribution in small glass tubes [5]. This method was also employed by Uddin and Inaba to measure the surface velocity of natural debris flow [9]. Our purpose is to provide accurate velocity information for vehicle self-contained navigation system [2].

The main research interest in a spatial filtering velocimeter has been focused on the design of the spatial filter, on which the signal quality primarily depends. An amplitude-modulated reticle constructed by a liquid crystal cell array was employed as spatial filter by Itakura [10]. A transmission grating was used as a spatial filter to measure flow velocity in a microscopic region [5,11]. Almost at the same time, a lenticular grating velocimeter was established by Ushizaka [12]. All the three filters mentioned above are used only as a filter, so an extra use of a photodetector is indispensable. In this paper, an area CCD spatial filter is applied to measure the velocity of solid-state surfaces. Because CCD can operate both as spatial filter and as photodetector, the system configuration is reduced noticeably.

The layout of this paper is as follows. The principle of the spatial filtering method is explained explicitly in the next section. Then section three shows how an area CCD acts both as spatial filter and as detector and investigates theoretically the characteristics of the spatial filter constructed by CCD. Section four first presents the experimental setup, which was used to measure the velocity of the side surface of a turn table and examined the possibility of spatial filtering velocimetry using an area CCD, and then experimentally studies the characteristics of the spatial filter in the aspect of the number of spatial period.

2. Principle of the spatial filtering method

The principle of the spatial filtering method is shown schematically in Fig. 1. When light rays illuminates a solid surface, which

---

* Corresponding author.
E-mail address: wthexin@gmail.com (X. He).

http://dx.doi.org/10.1016/j.ijleo.2014.08.084
0030-4026/© 2014 Elsevier GmbH. All rights reserved.

Please cite this article in press as: X. He, et al., Velocity measurement for moving surfaces using spatial filtering method based on area image sensor, Optik - Int. J. Light Electron Opt. (2014), http://dx.doi.org/10.1016/j.ijleo.2014.08.084

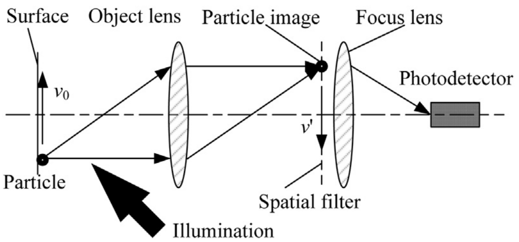


Fig. 1. Basic principle of spatial filtering method for measuring solid-state surfaces.

is usually rough due to random and finite sizes of particles, some of them are scattered by random particles in the solid surface. The scattered light rays are collected by the object lens so that random particles are imaged on the spatial filter, which is placed on the image plane. So the image on the spatial filter has property information of the surface. If a particle on the surface has a velocity of v_0 perpendicular to the grating slits of the spatial filter, the corresponding particle image has a velocity of v' vertical to the slits. Thus, $v' = Mv_0$, where M is the magnification of the imaging system with the object lens. Assuming that the particle images are smaller than half of the interval of the slits denoted by p, the total light intensity collected by the focus lens is temporally periodical due to the motion of the particle. And the periodical light intensity is focused on the detector, which is placed on the focal plane of the focus lens. As a result, the output of the detector contains a temporal frequency f relative to the velocity of the particle on the surface. If the moving direction has an angle of θ to the grating slits, the relation of the particles' velocity v_0 and the temporally frequency f could be determined as follows:

$$f = \frac{1}{p} M v_0 \cos\theta \tag{1}$$

It can be easily concluded that frequency of f is proportional to the particle velocity v_0. When the optical configuration of the whole system is determined, p and M are specified. Therefore, the velocity of the surface can be obtained when the light intensity frequency f is calculated.

3. Realization of the spatial filter using CCD

3.1. Spatial filtering characteristic of the CCD-type filter

A CCD is equivalent to a photodiode array, each pixel acting as an element photodiode. For simplicity, we just take linear CCD for example in this paper. As shown in Fig. 2, a set of odd pixels of the CCD is like a set of grating slits, so it consists of a spatial filter, denoted by SF1. What is more, these pixels also can receive light rays, just like the photodetector in Fig. 1. In the same way, a set of even pixels of the CCD consists of another photodetector and spatial filter, denoted by SF2.

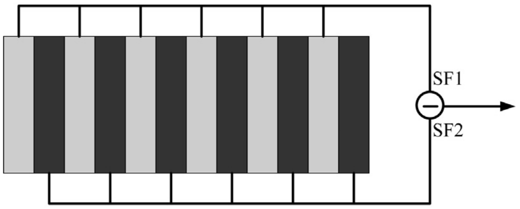
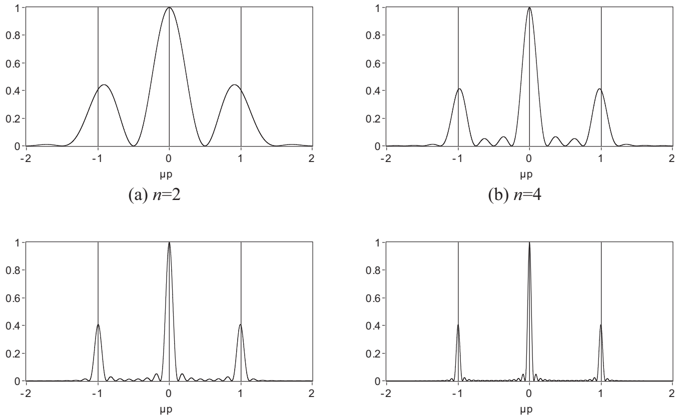


Fig. 2. Schematic diagram of CCD used as a differential spatial filter.



(a) n=2 (b) n=4

(c) n=8 (d) n=16

Fig. 3. Power spectra $|T(\mu)|^2$ for a spatial filter constructed by CCD depicted in Fig. 2 with four different spatial period n.

Assuming that the linear CCD has a size X in the x direction, and is infinite in the y direction for calculation simplicity, the amplitude transmittance function of SF1 can be given by

$$t(x) = \begin{cases} 1, & 0 \le 2mb \le x \le (2m+1)b \le X, \\ 0, & \text{otherwise.} \end{cases} \tag{2}$$

where m is zero or a positive integer, and b is the size of each pixel in x direction. The amplitude transmittance function of SF2 is similar to (2) with only a difference of phase of π. Thus, the power spectrum of (2) is derived as [13]

$$\left|T(\mu)\right|^2 = \left(\frac{\sin\pi\mu np}{n\sin\pi\mu p}\right)^2 \left(\frac{\sin\pi\mu\omega}{\pi\mu p}\right)^2 (np)^2 \tag{3}$$

where $T(\mu)$ is the modulation transfer function of SF1 and $X = np$ is used. The parameter p represents the spatial period of the SF1, in this case $p = 2b$. While the parameter n represents the number of spatial period included in length X.

Fig. 3 illustrates the power spectra $|T(\mu)|^2$ for a spatial filter constructed by CCD depicted in Fig. 2, numerically computed for four different numbers of spatial periods n. These spectral demonstrate narrow-band peaks at $\mu = 0$ and around $\pm 1/p$. For actually observed temporal signals, the positive frequency domain makes sense in the power spectrum. Thus, the spatial filter selects two spatial frequency components of $\mu = 0$ and around $1/p$. As seen from Fig. 3, the central frequency of the peak spectrum deviates form $\mu = 1/p$, which is used to calculate the temporal frequency f in Eq. (1). The peak deviation becomes smaller for a larger number of spatial period n. For $n = 8$ and 16, the peak deviation can be neglected even for accurate measurements. The deviation makes the peak locate at $\mu < 1/p$. Therefore, take the deviation into account, Eq. (1) can be deduced as follows

$$f = \frac{d}{p} M v_0 \cos\theta \tag{4}$$

where $d \le 1$ means the deviation from $\mu = 1/p$, and $d = 1$ means the deviation is zero. For simplicity, Eq. (4) is written as

$$f = k v_0 \tag{5}$$

where $k = dM\cos\theta/p$ denotes the scaling factor between surface velocity and signal frequency. The more the peak deviates from $\mu = 1/p$, the smaller k we will get. In addition, it is also seen from the figure that the spectral bandwidth of the signal component centered at $\mu = 1/p$ becomes small with an increasing number of spatial periods n.

Please cite this article in press as: X. He, et al., Velocity measurement for moving surfaces using spatial filtering method based on area image sensor, Optik - Int. J. Light Electron Opt. (2014), http://dx.doi.org/10.1016/j.ijleo.2014.08.084