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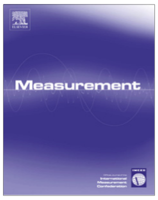

Spatial filtering velocimeter using frequency shifting by the method of rotating kernel

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A R T I C L E I N F O

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A B S T R A C T

A new approach of frequency shifting by rotating kernel is proposed to improve the performance of a spatial filtering velocimeter, used to provide accurate velocity information for a vehicle self-contained navigation system. A linear CMOS image sensor was employed both as a spatiotemporal differential spatial filter and as a photodetector. The filtering operation was fully performed in FPGA and is realized by applying a rotating kernel to the pixel values of the image. Theoretical analysis showed this method could double the maximum measurable velocity. The power spectrum of the output signal was obtained by fast Fourier transform (FFT), and was corrected by a frequency spectrum correction algorithm, named energy centrobaric correction. This velocimeter was used to measure the moving velocities of a conveyor belt. Experimental results verified the method's ability of reducing the output signal frequency and standard uncertainty of velocity measurement. What is more, the undesired output introduced by frequency shifting to the power spectrum of the output signal was deeply investigated and a new method was proposed to eliminate the undesired component in output signals. This velocimeter aims at providing accurate velocity information for vehicle autonomous navigation system.

1. Introduction

The demand for reliability of autonomous navigation systems is increasingly high. The navigation system needs to be fully autonomous and should be able to continuously position with high accuracy. However, in vehicle autonomous navigation systems, the velocity information is presently provided by accelerometers, which have divergent trends over time. Therefore, the idea of using a velocimeter to measure the velocity for the vehicle autonomous navigation system was put forward [1]. There are some methods of optical velocity measurement, such as laser Doppler velocimetry, laser speckle velocimetry and spatial filtering velocimetry. These methods have all been used to measure the velocity of vehicles relative to ground surfaces [1–4]. Therefore, all of them have the potential for application to vehicle autonomous navigation systems. However, the first two methods using laser as the illumination cannot satisfy the requirements of reliability at high ambient temperature, long life of its light source and reasonable cost, whereas the spatial filtering velocimeter can meet with all the requirements above.

In spatial filtering velocimetry the spatial filtering device is the most important element. There are roughly four types of spatial filters being applied to the spatial filtering velocimeter [5]: transmission grating type [6], detector type [7,8], optical fiber type [9] and other special grating type [10–12]. A detector type of spatial filtering device, a linear image sensor, is used in our system. The image sensor operates both as a spatial filter and as a photodetector. However, the frame rate limits the maximum detectable velocity, making the measurement range unable to cover all the velocities of the vehicle. Although an

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operation, known as pixel binning, can be used to increase frame rate [13,14], the sophisticated clocking makes the system design much more complicated. Most importantly, not every type of image sensor is equipped with the function of pixel binning. In this paper, a new approach of frequency shifting by rotating kernel is proposed to increase the maximum detectable velocity. This new method is similar in concept to the system of a liquid crystal transmission filter with amplitude-modulated reticle used by Itakura et al. [15]. Through this method, the upper limit of measurable velocity can be doubled, which is of great significance when the vehicle is moving at very high speeds. What is more, this method can greatly reduce the relative standard uncertainty. The built velocimeter was used to measure the velocities of a conveyor belt driven by a high precision and stability rotary table, which has rate stability better than 0.001% of commanded rate measured over one revolution. The experimental results show that this system using the method of rotating kernel has good potential of application to the vehicle self-contained navigation system.

2. Principles of spatial filtering velocimeter

2.1. Basic principle of spatial filtering velocimeter

The basic principle and optical system of the spatial filtering velocimeter for a vehicle are shown schematically in Fig. 1. The velocimeter is deployed in the vehicle to measure the relative velocity v between the vehicle and the ground surface. An LED, an active light source, is employed to illuminate the ground surface. Part of the illuminating light rays are scattered by particles on the moving surface and are collected by the object lens so that the surface can be imaged onto a spatial filter that has spatially periodic transmittance in the moving direction of the surface. The total light intensity collected by the focus lens is temporally periodic due to the motion of the ground surface. Then the time-periodical light intensity is fed into the photodetector. As a result, the output of the photodetector contains a temporal frequency f relative to the velocity v of the vehicle. Then the relationship between the vehicle's velocity v and the temporal frequency f could be determined as follows:

$$v = \frac{p}{M} f, \tag{1}$$

where p is the spatial period of the spatial filter, and M is the magnification of the imaging system consisting of the object lens.

2.2. Detector type spatial filtering velocimeter

The mathematical model for a detector type spatial filtering velocimeter is shown in Fig. 2. The detector type spatial filter is placed at the image plane. The moving objects are imaged by the imaging lens onto it. Let $p(x,y,t)$ be the light intensity distribution of the moving image, which is time-dependant, in the x–y plane before the spatial filter and $q(x,y)$ the weighting function of the spatial filter. Then the filtered light intensity $g(x,y,t)$ is given by the convolution integral as:

$$g(x,y,t) = \int\int p(x,y,t) \times q(x,y) dxdy, \tag{2}$$

which is performed digitally after the acquisition of the moving image by

$$S(t) = g(t) = \sum_r P(r,t) Q(r), \tag{3}$$

where r is the number of the pixel in the image, $P(r,t)$ is the grey values of pixels and $Q(r)$ is the weighting function. Eq. (3) can be represented by the following matrix multiplication

$$S = P_{1\times r} \cdot Q_{r\times 1}, \tag{4}$$

where $P_{1\times r}$ is a matrix consisting of all the image pixel values arrayed spatially sequentially and $Q_{r\times 1}$ is the weighting matrix.

The multiplication of Eq. (4) with a differential weighting matrix is schematically shown in Fig. 3. In Fig. 3 white and grey strips represent pixels of a linear image sensor, which has r pixels. n neighboring pixels form one group which corresponds to a transparent or opaque bar of a transmission grating type spatial filter. Here the values of +1 (shown in white) and -1 (shown in grey) form two filters which can be summed up respectively to generate signals S_1 and S_2. Due to the spatially π-phase difference of

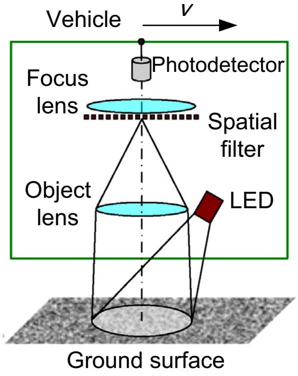

Fig. 1. Basic principle and optical system of the spatial filtering velocimeter for a vehicle.

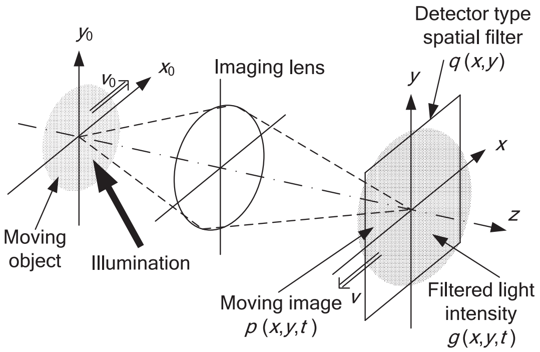

Fig. 2. Mathematical model for a detector type spatial filtering velocimeter.