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INVESTIGATION OF PRECISION TRANSPORT ADAPTIVE CORRELATION VELOCIMETER

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In connection with developing autonomous automatic control systems of vehicles the requirements upon the accuracy of movement parameters measurement are risen. Mechanical devices for indirect measurement, converting the measured rate of wheel rotation into the estimation of the linear velocity and other motion parameters, often work with great errors. It explain the interest to develop new nonmechanical direct measuring speedometers. One of them is the adaptive correlation velocimeter (ACVM), tracking with great accuracy the transport delay between signals from two optical-electronic sensors, allocated along the velocity vector and aimed on the illuminated road surface. By mathematical modeling of the ACVM signal processing unit, simulation of the surface and laws of sensor moving above it, the influence of undesired mechanical disturbances and receiving channels nonidentity on the accuracy of measurements was investigated. It was also established that the use of an anisotropic spatial input signal filtration allows to increase the accuracy of measurements.

K e y w o r d s: Velocimetry, adaptive correlation meter, ACVM, anisotropic sensor aperture.

1 INTRODUCTION

Nowadays there are a lot of mechanical and electronic devices for autonomous speed measurement of vehicles. These devices compete with each other as for the accuracy of measurement, calcul0ation speed, manufacturing simplicity, cost and so on. The mechanical speedometers of indirect measurement actually measure the angular rotation speed of a driving wheel and, hence, the wheel diameter variations and sliding lead to errors in estimation of vehicle's linear speed. These errors often surpass allowable standards. It hinders automation of vehicle's control and stimulates development of new, more exact monitoring systems of motion parameters.

A number of companies as Alcatel, Corrsys [4] and others are engaged in solving this problem but speedometers offered by them are either very expensive or have restrictions on accuracy or working conditions.

Considered in the given article, the adaptive correlation velocimeter (ACVM) is an exact and less expensive device for ground vehicles. Its operation is based on estimating the mutual shifts of signals from two optical gauges placed along the speed vector and directed on a non-uniform spreading surface [1, 5].

Adaptation of the ACVM is achieved by sensitivity normalization of a correlation discriminator, and time-and-frequency scaling of linear filters in a tracking contour. Due to this in a tracking mode the calculation rate of ACVM always corresponds to the moving speed, and the optimum accord between the spectrum of signals and frequency response of ACVM in all range of measuring speeds is supported.

Under condition of optical gauges of sufficient identity and parallelism of their optical axes, primary factors which influence the accuracy of ACVM can be the speed vector tangential deviations from the direction of the coupled gauges base because of transversal disturbances of the moving vehicle.

The structure and operating principle of ACVM is described in the second section. The third section is devoted to the behaviour of the tracking ACVM at different movement laws of the coupled gauges with anisotropic apertures above a two-dimensional field of brightnesses. In the fourth section the influence of sensitivity distinction of ACVM's optical channels on the accuracy of speed measurement is described.

2 STRUCTURE AND OPERATING PRINCIPLE OF ACVM

Optical beams, being reflected from a spreading surface over which the device moves, are focused by reception lenses on photodetectors D1 and D2.

The photodetectors are located at a certain distance from each other (see Fig. 1). In front of photodetectors diaphragms may be placed which define the projection forms of the gauge's sensitive elements on the surface. Knowing the distance between optical gauges and having measured the delay between signals from D1 and D2, it is possible to calculate the speed of movement of the device over the surface. A block diagram of ACVM is given in Fig. 2.

At a movement of the scalar field in direction $\vec{z}(z_1, z_2)$ an electric signal on the output of each optical gauge arises. The gauges, besides transformation function of the

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optical signal into electric, are linear spatial filters. Each signal from D1 and D2 is determined by convolution of brightness field spatial function B with aperture function of the gauge G.

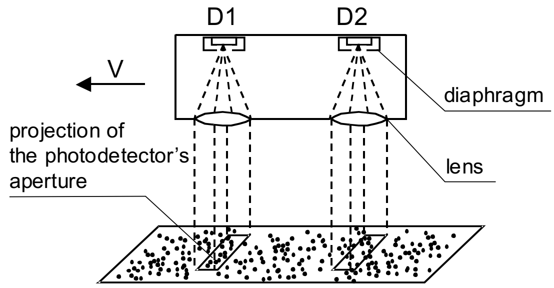

Fig. 1. Optical module of ACVM.

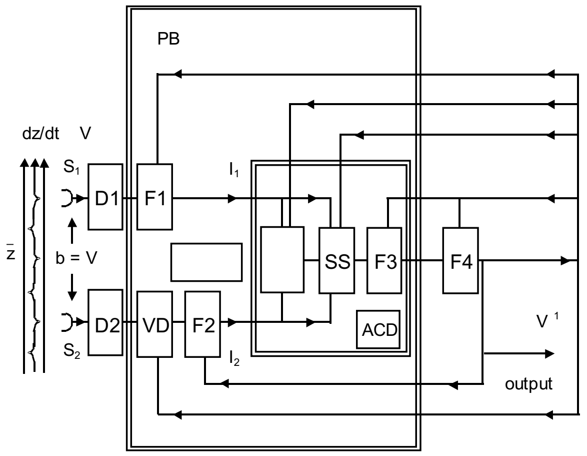

Fig. 2. Generalized block diagram of ACVM.

The signals from the coupled gauges enter the processing block PB through filters F1 and F2 providing their mutual orthogonality (under condition that the delays brought by filters are identical and an artificial delay brought by variable delay block VD completely compensates the transport delay between S_1 and S_2). Outputs of F1 and F2 are passed into the adaptive correlation discriminator ACD. It consists of a multiplier, sensitivity stabilizer SS and filter-accumulator F3. An error signal from the ACD through the correction feedback filter F4 controls the time delay between the input signals.

The results given below are obtained under condition that filter F4 is an integrator and F3 is an FIR. At such a choice of filters the model of ACVM, in a steady mode, approximates the tracking contour with the first order astaticism. It works with a zero error on average when ACVM estimates a constant speed at any point of the measurement range.

3 THE INFLUENCE OF TRANSVERSAL MECHANICAL DISTURBANCES

For simulation of input signals obtained from the pair of optical gauges a convolution of delta-correlated two-dimensional “white” noise with two-dimensional weighted Gauss function was used:

$$G = \exp\left(-\alpha\zeta_1^2\right)\exp\left(\beta\zeta_2^2\right).$$

As the initial field is the two-dimensional “white” noise, the correlation properties of the resulting surface are determined by correlation properties of the weight function only. In particular, for the Gauss weight function the expression for correlation interval on one axis in discrete representation is [2]:

$$\Delta(s) = \frac{\left\{\sum_{n=0}^{N}\left[\exp\left(-\alpha\left(n-\frac{N}{2}\right)^2\right)-1\right]\right\}^2}{\sum_{n=0}^{N}\left[\exp\left(-2\alpha\left(n-\frac{N}{2}\right)^2\right)-1\right]},$$

where N is the number of weight function sample, and a is a parameter of the Gauss function.

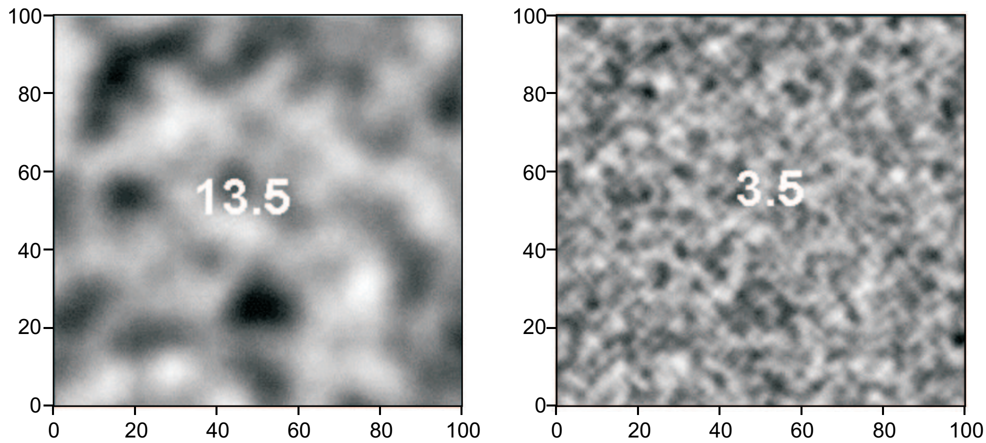

Fig. 3. Examples of spreading surfaces

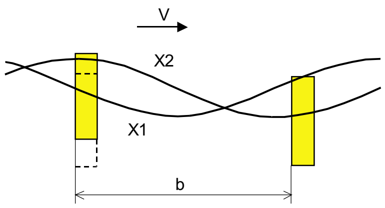

Fig. 4. The signal decorrelation because of transversal fluctuations of the speed vector

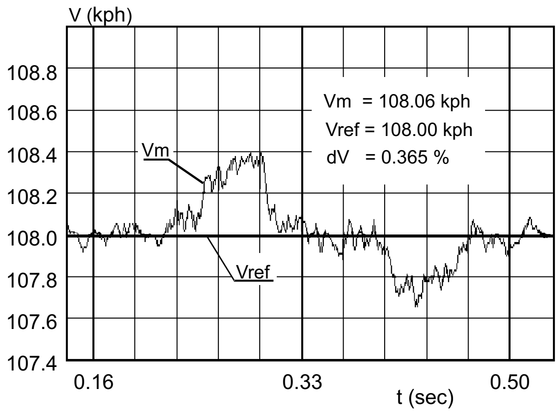

Fig. 5. The tracking a constant speed by ACVM at presence of transverse fluctuations with amplitude 4 mm and size of input apertures $10 \times 10\,\mathrm{mm}^2$.

The surface examples, obtained by this method, with correlation intervals of 3.5 and 13.5 mm (Here and further the size of each surface pixel equals 1 mm.) are reproduced in Fig. 3.

The signals S_1 and S_2, formed by optical gauges from these surfaces are determined by convolution of their aperture characteristics with respective elements of the surface with subsequent normalization to guarantee a constant dispersion of their random structure. Due to this in experiments the conditions close to reality were reproduced, where the width of autocorrelation function (ACF) and the effective power of signals incoming to the correlator through rebuilt filters could vary over some orders of magnitude. It allows to estimate the robustness of the used algorithm.

The aperture function of each gauge in general is represented by sensitivity factors of the system photodetector-diaphragm-lens in each point of the observed area on the spreading surface. In our research it was considered that the aperture function of the optic channels is a two-dimensional rectangular window function of size $(k \times l)$.

$$H(\xi_1,\xi_2) = \begin{cases} 1\,, & |\xi_1| \le k\,,\ |\xi_2| \le 1 \\ 0\,, & |\xi_1| > k\,,\ |\xi_2| > 1 \end{cases}$$

This assumption is lawful if the diaphragm passes paraxial beams only and on the surface a precise "image" of return projection of the photoreception channel aperture function is formed. At modelling with the purpose of qualitative estimation of the expected effect of anisotropic spatial filtration of signals in ACVM it is meaningful to use the simplest "window" aperture functions.

The signal value in a given point of the spreading surface is determined by two-dimensional convolution of the aperture function H with the spreading brightness field B:

$$S = W^{-1}(B \otimes H)\,,$$

where W is the window area, $\otimes$ is a symbol of two-dimensional convolution. The form and sizes of the gauge aperture H play a significant role in speed measurement accuracy. The developed program models allow to model the signals received from the surface, in view of nature of movement and the form of gauges's apertures.

Let us consider the mechanism of occurrence of mechanical decorrelation disturbances with reference to railway vehicles, where besides longitudinal movement also transversal fluctuations take place. These fluctuations contribute by an essential part to the speed measurement error as their amplitude can reach several centimeters (about 3 cm at a frequency 0.7 Hz. (experimental data)), and in some cases can exceed the correlation interval of the spreading surface. As the tests described in [3] have shown, the main spectrum of the railway vehicle transversal fluctuations is ranges from 0.5 Hz up to 3 Hz. These fluctuations are caused by different reasons but in general they arise because of conical bandages of wheels and railway deterioration.

Let us consider a simple case of harmonic fluctuations of the pair of gauges. It is possible to estimate the signal decorrelation value via estimation of the mutual of shift apertures (in projection to the spreading surface) while the gauges move with speed V. Let in the moment t the measuring device occupy some initial position in space. In time interval b/V, where b is the base of ACVM, and V is the speed of movement, the aperture projection displacement of one of gauges with respect to another one will be:

$$\begin{aligned} \Delta l &= A\,[\sin(2\pi f t_2) - \sin(2\pi f t_1)] \\ &= 2A\cos\Big(\pi f\frac{b}{V}\Big)\sin\Big(\pi f\frac{b}{V}\Big)\,, \end{aligned}$$

$$t_2 - t_1 = \Delta t = \frac{b}{V}\,, \qquad t_1 = 0\,,$$

where f is the frequency of transversal fluctuations, A is its amplitude.

It is meaningful to apply anisotropic spatial filtration of input signals to compensate the influence of transversal displacement. In other words — it is necessary to extend the input apertures of photodetectors in the transversal direction. This measure allows to decrease the influence of the speed vector's transverse variation. The value of input signals decorrelation depends on the relative shift of the apertures projection $\frac{\Delta l}{l}$, where l is the aperture transverse size (the large side of the aperture). (See Fig. 4).

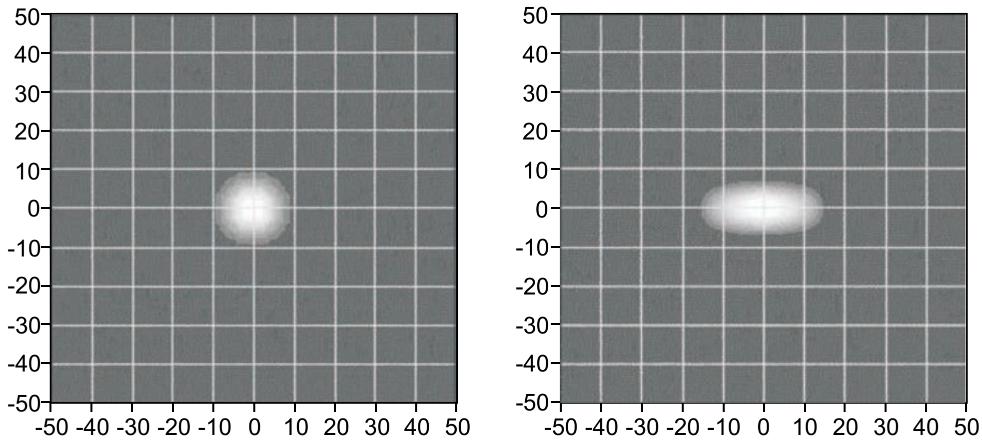

Fig. 6. The autocorrelation functions of the original surface with correlation interval 13mm (left) and of the surface, filtered by bidimensional rectangular window 30x10mm (right)

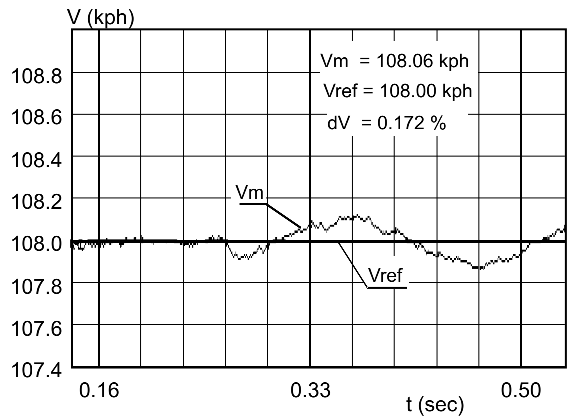

Fig. 7. The tracking a constant speed by ACVM at presence of transverse fluctuations with amplitude 4 mm and size of input apertures $10 \times 30\,\mathrm{mm}^2$.

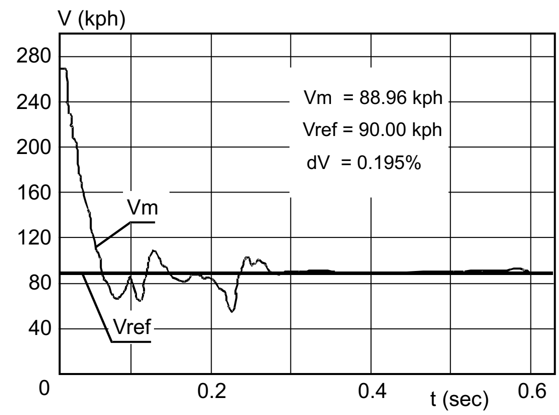

Fig. 8. The tracking a constant speed by ACVM at nonidentity of optical channels — 2 %

In the experiments described below the spreading surface has a correlation interval of 50 mm as this size corresponds to the characteristic size of railroad macadam. This size determines the choice of the photodetectors aperture size so as, on the one hand, not to smooth the input signal by the spatial filters, and to compensate the influence of transversal fluctuations on the measuring device on the other hand.

When modelling the device movement with a speed of $V = 30$ mps (108 kph), the amplitude of transverse fluctuations 4 mm and the size of the aperture projection $10 \times 10\,\mathrm{mm}^2$ (the transversal fluctuations amplitude and size of the photodetector's aperture projection are expressed in pixels of the surface.) the diagram of tracking by ACVM the constant speed is in Fig. 5.

In Fig. 5 V_{ref} is the original speed of the device over the surface, and V_m is its estimation. This difference between the true speed and its estimation can be reduced by application of anisotropic spatial filtration of input signals.

The comparison of autocorrelation functions of the initial surface and an equivalent surface filtered by the rectangular spatial filter (Fig. 6) shows that the cross size of the second ACF's maximum will define the allowable amplitude of transverse fluctuations, at which the catching new elements of the surface by the optical receiver in its vision range will be almost unnoticeable.

As the filtered surface was made by convolution of two-dimensional white noise $B(x,y)$ with the spatial Gauss filter $G(x,y)$, the ACF of the surface filtered by two-dimensional window aperture function $H(x,y)$ will be [6]:

$$A = (\check{H} \otimes \check{G} \otimes \check{B}) \otimes (H \otimes G \otimes B) = (\check{H} \otimes H) \otimes (\check{G} \otimes G) = A_H \otimes A_G \,,$$

where the symbol ˇ means sign inverting of arguments x, y; A_H and A_G — ACFs of H and G filters accordingly.

Comparing the behaviour of ACVM in the presence of the same transversal fluctuations as in the previous experiment but with extended apertures of photodetectors, we shall see that the error of speed measurement has decreased twice (Fig. 7).

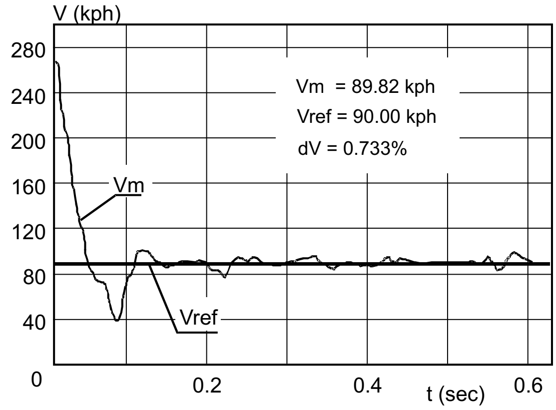

Fig. 9. The tracking a constant speed by ACVM at nonidentity of optical channels — 15 %

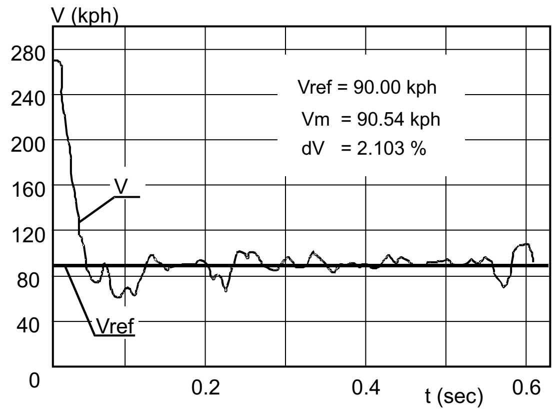

Fig. 10. The tracking a constant speed by ACVM at nonidentity of optical channels — 30 %

Studying the behaviour statistics of ACVM in the presence of such mechanical fluctuations shows that the effect of application of anisotropic spatial filtration twice almost allows to decrease the speed measurement error.

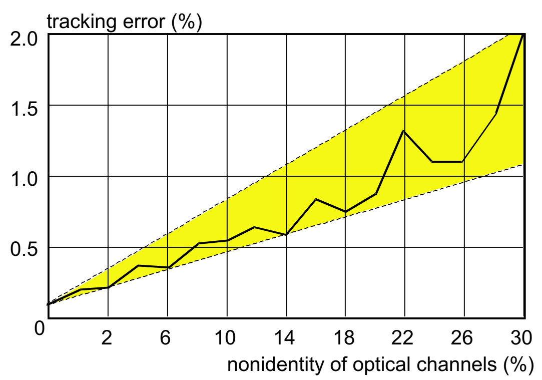

Fig. 11. Dependence of the root-mean-square error of speed measurement on sensitivity nonidentity of optical channels

4 THE INFLUENCE OF SENSITIVITY NONIDENTITY OF ACVM'S OPTICAL CHANNELS ON THE ACCURACY OF SPEED MEASUREMENT

Nonidentity of the ACVM optical channels may arise because of a change in their electric parameters or as a result of optics impurity. The property of the device is that the nonidentity of the channels results in appearance of noise on the output of the discriminator at zero shift between signals. The dispersion of the noise is directly proportional to the nonidentity factor $k = \frac{|\mu_1 - \mu_2|}{\mu_1}$, where μ_1 and μ_2 are sensitivities of the first and the second channels.

The influence of sensitivity nonidentity of optical channels on the speed measurement accuracy is shown in Figs. 8, 9 and 10. Here the process of entering the device in a tracking mode after its power turned on is also shown. All data on these diagrams are obtained using the square aperture of optical gauges ($10 \times 10\,\mathrm{mm}^2$) for the speed 25 mps (90 kph).

From modelling results one can see that the system remains efficient even if a significant difference in sensitivity of ACVM channels takes place. It emphasizes the robustness of the used operating principle.In Fig. 11 the average dependence of root-mean-square speed measurement error (in steady-state mode) on nonidentity factor k is shown. The form of each particular dependence (example is given on the diagram) is determined by realization of an input random signal, therefore it is meaningful to speak only about their distribution. The measurement of error dV is begins from the time moment 0.3 sec., after which the tracking mode was considered steady-state.

5 CONCLUSION

The studying of ACVM carried out in this article has shown:

1. In the presence of external mechanical decorrelation disturbances, the application of anisotropic spatial filtration decreases the speed measurement error. In the considered case the error decreases almost twice.
2. The robustness of tracking contour allows the sensitivity nonidentity of ACVM's optical channels up to 10 %. So, in the considered example at such nonidentity the error did not exceed 0.5 % of the measured value.

These results may be generalized to other applications of ACVM, distinct from railway vehicles. It is obvious that if the sizes of gauge apertures change proportionally to the change of the correlation interval of the surface and the amplitude of transversal fluctuations, than the speed measurement error will remain intact.

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