COMPUTER AIDED MODELLING OF STOCHASTIC SIGNALS USED IN MEASUREMENTS OF TRANSPORT PARAMETERS BY STATISTICAL METHODS

© *Hanus R., 2003*

Rzeszów University of Technology, Department of Metrology and Measurement Systems 2B, W. Pola Street, 35 -959
Rzeszów, Poland

In the paper, application of the DASYLab software for modelling of signals received from sensors in statistical measurements of parameters of transport of solid bodies, liquids, and other media transported by means of pipelines is described. Cross-correlation functions of the generated signals were determined and compared to those observed in real signals.

1. Introduction. Measurements of transport parameters of solid bodies and media (powders, liquids, gases) in pipelines and open ducts can be realised by means of both deterministic and statistic methods. The first group of methods is used in cases when the sensors deliver determined signals characterised with parameters being functions of measured quantities. However, in many cases, e.g. in multiphase media (mixtures of liquids and solid particles in pipelines or those of gas and solid particles in pneumatic transport), the measurement has to be performed by means of contactless methods and acquisition of determined signals is not possible. Additional problem consists in different velocities of motion of different medium phases. Signals obtained from sensors (in most cases from capacitance, ultrasonic, optical, thermal, or radiation ones) in such measurements are usually stochastic. In these cases, and also in some contactless measurements of velocity of solid bodies, e.g. of metal sheets and strips during rolling, methods based on statistical analysis of signals can be useful. In the literature, the cross-correlation method is one of the most frequently discussed [1–5, 10, 18, 20], and in other cases, use of phase of the cross-spectral density function [1, 2, 20] and other functions [4, 10, 12] is also possible.

Velocity measurement in case of rolling of metal sheets, or bars by means of statistical methods is a problem much simpler than the measurement of flow velocity. Using two sensors, located at a distance d along direction of motion of the object, one makes use of models of stochastic signals $x(t)$ and $y(t)$ by taking into account only the time shift τ_0 or small disturbance of the delayed signal $y(t)$ [5–7, 12, 13, 17]. Respective discrete models of signals generated in transducers under assumption of linear processing can be represented by means of the following expressions:

$$y(n) = a \cdot x(n - l_0), \quad (1)$$

$$y(n) = a \cdot x(n - l_0) + z(n), \quad (2)$$

where $x(n)$ — discrete model of real, zero-mean, normal stationary signals, t_n — discrete values of time; Δt — sampling step; $a \approx 1$ — the attenuation factor between the sensors; $l_0 = \tau_0/\Delta t$ —discrete value of the time delay; $z(n)$ — corrupting noise of normal distribution $N(0,\sigma_z)$ not correlated with signals $x(n)$ i $y(n)$.

In case of pneumatic transport of liquid/solid particles mixtures, powders, or granulates, the flow is frequently of turbulent character, which results in significant differences between signals obtained from sensors located at relatively small distance from each other. The models of signals can be in such case represented by means of the expression [12]:

$$y(n) = a \cdot x(n - l_0) + f_1(l_0) \cdot z(n), \quad (3)$$

where: $f_l(l_0)$ — value at point $l = l_0$ of a function chosen so that required character of main extreme amplitude variation of cross-correlation function at variable delay can be obtained.

When modelling signals, apart from the assumed delay model, e.g. this expressed by (1), one has to take into account dependence of signals spectra on various velocities of the object. This problem for some models used in case of transport of solid bodies has been analysed in [8], where it was shown that increase of the object velocity results in respective decrease of signal correlation interval, which in turn gives steepest pattern of its auto-correlation function. In the present paper it is assumed that the velocity of the object does not change in the course of the measurement, thus the obtained signals are stationary. Some models of random non-stationary signals, obtained in case of transport of rigid solid bodies, were presented in [7].

The aim of the work described in the present paper was to obtain signal models that would correspond to real signals obtained from transducers in measurements of solid bodies, liquids, and multiphase media transport parameters performed by means of statistical methods. As the most frequently used (and described in the literature) characteristics in medium transport velocity parameter measurements is the cross-correlation function, it has been assumed that the pattern of the function for models should be the same as this for real signals.

The concept of measurement of transport-induced delay by means of correlation method consists in determination of the estimator of normalised cross-correlation function of signals based on N values $x(n)$ and $y(n)$ from the expression:

$$\hat{\rho}_{xy}(l) = \frac{\dfrac{N}{N-l}\sum\limits_{n=0}^{N-l-1} x(n)y(n+l)}{\sqrt{\sum\limits_{n=0}^{N-1} x^2(n)\sum\limits_{n=0}^{N-1} y^2(n)}}. \tag{4}$$

The argument of main maximum of the cross-correlation function determines delay τ_0 that is a base for calculations of required transport parameters, namely: average velocity

$$V = d/\tau_0, \tag{5}$$

volume flux $Q = kVA$ (A — transversal cross-section area of the pipeline or duct; k —a coefficient accounting for the velocity distribution in the channel cross-section). The major problems in measurement of these parameters are inter alia: determination and account for medium velocity profile in the pipeline, and selection and proper positioning of sensors. These problems are discussed in details in the literature, cf. e.g. [1, 11, 18–20].

For the signal models given by (1–3), values of the normalised cross-correlation function in the maximum point and for $a = 1$ are respectively:

$$\rho_{xy}(l_0) = 1. \tag{6}$$

$$\rho_{xy}(l_0) = \frac{1}{\sqrt{1+\left(\dfrac{\sigma_z}{\sigma_x}\right)^2}}. \tag{7}$$

$$\rho_{xy}(l_0) = \frac{1}{\sqrt{1+\left(\dfrac{f_1(l_0)\sigma_z}{\sigma_x}\right)^2}}. \tag{8}$$

Given values $\rho_{xy}(l_0)$ obtained for specific medium from measurements carried out for several different delays, one can determine respective values of σ_z/σ_x and of function $f_1(l_0)$ by means of transformation of equations (7–8) into the form:

$$\frac{\sigma_z}{\sigma_x} = \sqrt{\left(\frac{1}{\rho_{xy}^2(l_0)} - 1\right)}. \tag{9}$$

$$f_1(l_0) = \frac{\sigma_x}{\sigma_z}\sqrt{\left(\frac{1}{\rho_{xy}^2(l_0)} - 1\right)}. \tag{10}$$

As values of σ_x/σ_z are not available in the course of measurements, in order to model signals according to (3) it is more convenient to use a transformation of formula (10):

$$\frac{\sigma_x}{f_1(l_0)\sigma_z} = \frac{1}{\sqrt{\left(\dfrac{1}{\rho_{xy}^2(l_0)} - 1\right)}}. \tag{11}$$

2. Modelling of measurement signals from transducers. Interesting research possibilities are created by means of use of computational technique for creation of discrete signal models (1–3) and than for statistical analysis of these models by means of specific algorithms. In [6] it was shown that computer based pseudo-random number generators are useful in modelling typical signals obtained from sensors in measurements of transport parameters by means of statistical methods. Currently available software offers great possibilities in this area; metrology engineers shall be interested e.g. in integrated environments for software control of measurement set-ups (presently the most popular packages are: LabYIEW, LabWindows/CVI, VEE, DASYLab, Test Point), which enable not only modelling, but also facilitate construction of measurement set-ups based on classic apparatuses or DAQ computer boards.

In the present paper, signal modelling and correlation were performed by means of the DASYLab software [9], which showed to be fully adequate for realisation of the task, relatively easy and intuitive to handle as well as able to co-operate with large selection of measurement boards offered by numerous manufacturers. Fig. 1 represents the diagram of the set-up, which served for modelling of signals according to formulae (1–3) and for determination of the normalised cross-correlation function.

Generation, shaping of the spectrum, and setting the selected delay model was realised by means of the following software modules: *Generator00–01, Filter00, Delay00* i *Formula00.* Required alterations of signal spectra is achieved by setting different cut-off frequencies of IIR low-pass filters in the *Filter00* module. Application of low-pas filtering provides also for required normalisation of probability distribution of amplitudes of the modelled signals and auto-correlation function patterns of these signals of the $(\sin x)/x$ type. Determination of the cross-correlation function is realised by the *Correlation00* module with use of FFT algorithms, which gives results analogous to those obtained by means of application of equation (3), but thanks to reduction of number of operations, shortens also the calculation time. Use of the averaging module *BlockAver00* as an option results in reduction of variance of the determined estimators, allowing for smoother correlation function pattern.

Thanks to DASYLab's built-in mechanisms, the set-up of Fig. 1 can be easily enlarged with data recording, transmission, and sharing options.

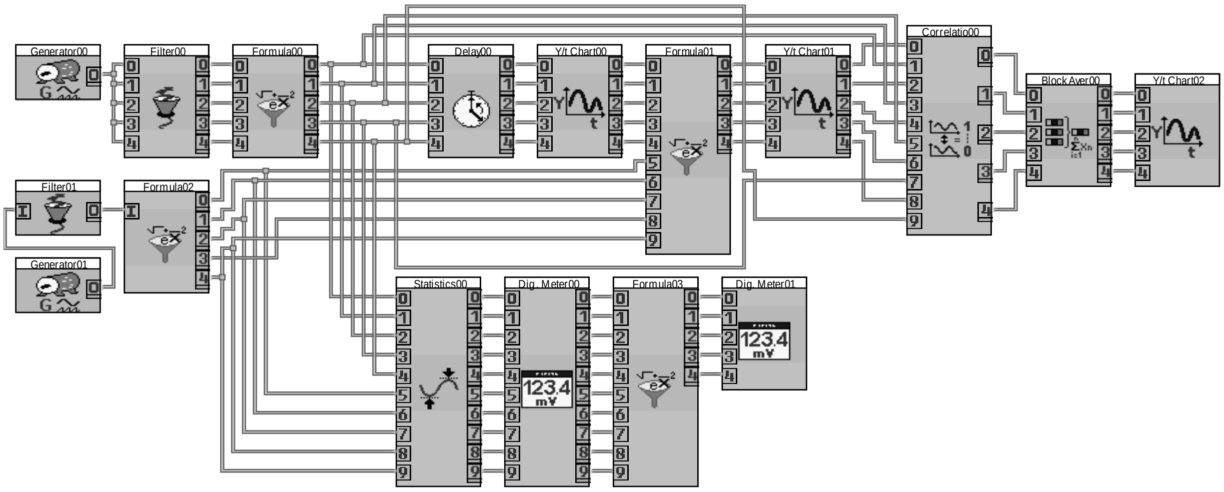
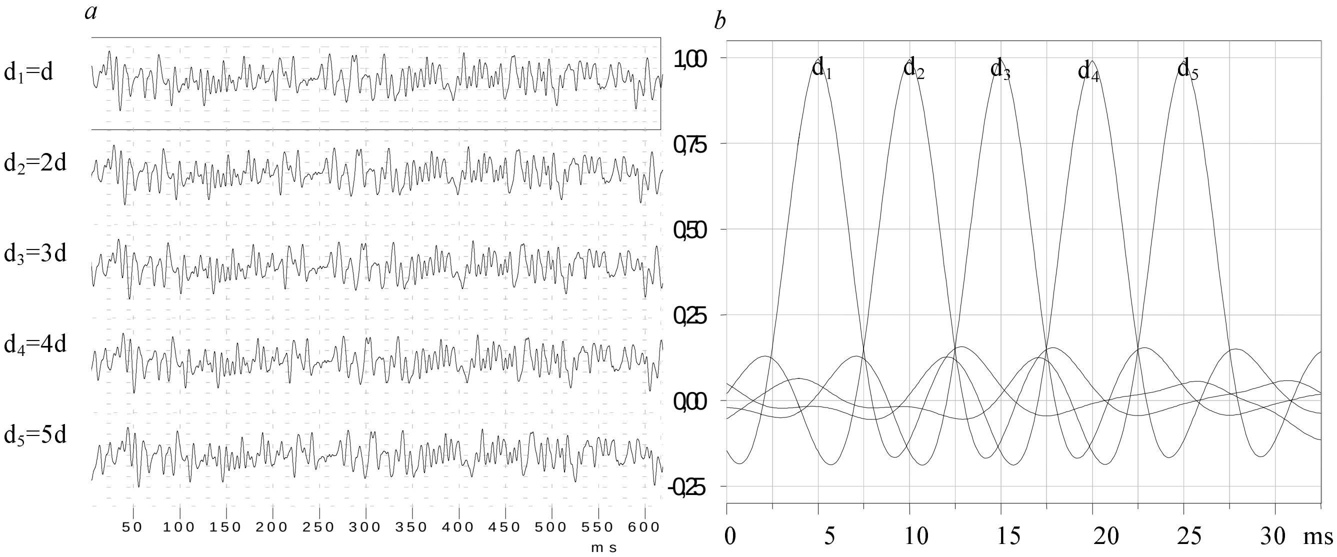


Fig. 1. Diagram of the set-up for modelling and correlation analysis of mutually delayed stochastic signals



Rys. 2. Przebiegi czasowe sygnałów (a) i funkcje korelacji wzajemnej (b) sygnałów modelowanych wg. zależności (1) dla stałej prędkości obiektu V i różnych odległości rozmieszczenia czujników d

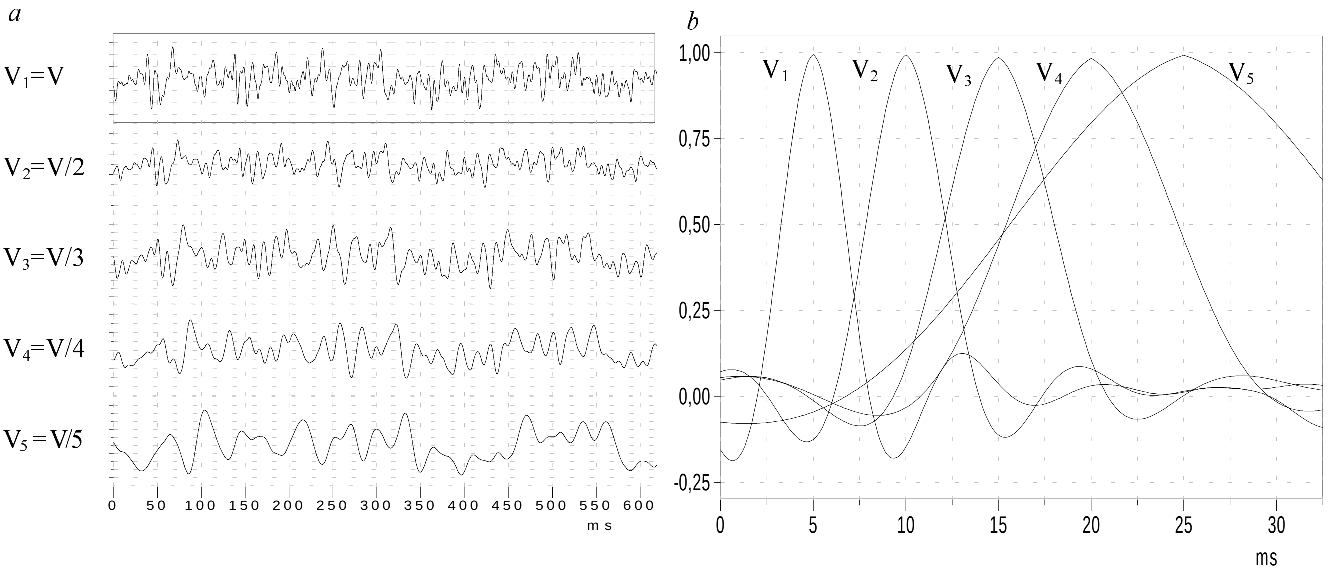


Fig. 3. Time patterns (a) and normalised cross-correlation functions (b) of signals modelled according to formula (1) for z(n) *= 0 and different values of* V *with distance between sensors assumed constant*

At Fig. 2, typical time patterns of the delayed signal (*l*) are presented as well as normalised cross-correlation functions obtained at $a = 1$. The same value of the coefficient $a = 1$ was adopted also for all signal models discussed in the following. Constant value of the velocity V was assumed, and thus, according to formula (5), changes in distance between locations of transducers can be simulated by means of setting proper values of τ_0. The delay values adopted for modelling were consecutively: 5, 10, 15, 20, 25 ms.

Fig. 3 represents examples of time patterns of delayed signal models (1) and cross-correlation functions (6), but for different velocities V. When modelling, changes in spectra of signals generated for subsequent velocities of the object have been taken into account.

Shaping of spectra of patterns presented in fig. 3 was obtained by means of the 4th order Buttwerworth filter with the following cut-off frequencies: 150, 120, 90, 60, and 30 Hz. By changing type and order of filters and their cut-off frequencies, as well as by choosing delays and global settings of the software, one can obtain required parameters of the modelled signals. According to relation (5), changes of V at constant distance d result in respective changes of τ_0. The delay values adopted for modelling were as follows: 5, 10, 15, 20, and 25 ms. The cases presented above can serve as comparison examples; in real life, correlation functions as those in figs. 2 , a and 2, b are rather exceptional (as representing a perfect situation) in correlation measurements of transport parameters of solid bodies.

In the literature [1–3, 12–18, 20] one can find a number of examples of cross-correlation functions, obtained in measurement of velocity of solid bodies and of media such as powders, liquids, and multiphase mixtures in pipelines and open ducts for specific types of sensors with variable measurement parameters. Analysis of these functions leads to the conclusion that in the course of modelling, one should take into account changes of signal spectra as in Fig. 3 and set properly values of parameters occurring in relations (2–3). In fig. 4, example time patterns of delayed signal models (2) are presented, as well as normalised cross-correlation functions (7) for different velocities of the object V with distance d assumed constant. The value of $\sigma_z/\sigma_x = 0.5$ has been adopted.

Patterns of the mutual correlation function similar to those presented in fig. 4,b are being obtained in measurements of solid bodies transport parameters. When modelling, changes in spectra of the generated signals were taken into account for consecutive object velocities analogously as for signals represented in fig. 3, b.

Another examples given in the following represent signal models generated in the set-up of Fig. 1 and their respective cross-correlation functions, similar to those obtained in real life in measurements of media like liquids and disintegrated solids. In fig. 5, signal time patterns obtained for the model described by (3) are presented as well as cross-correlation functions (8) under assumption of linear decrease of amplitude of main extreme of these functions for different distances between sensor locations.

With the assumption $V = \text{const}$, changes in d were simulated by means of setting the following delay values: 5, 10, 15, 20, and 25 ms. The assumed values of the ratio $\sigma_x/[f_l(l_0)\sigma_z]$ for consecutive delays were: 1.59, 1.32, 1.11, 1.01, and 0.97, respectively. The settings of the filters were analogous to those shown in fig. 3. The pattern of changes in cross-correlation main extreme amplitude, shown in Fig. 5b, corresponds to this observed for mixture of sand and metal shot in pneumatic transport. The measurement was realised with use of capacitance sensors [18].

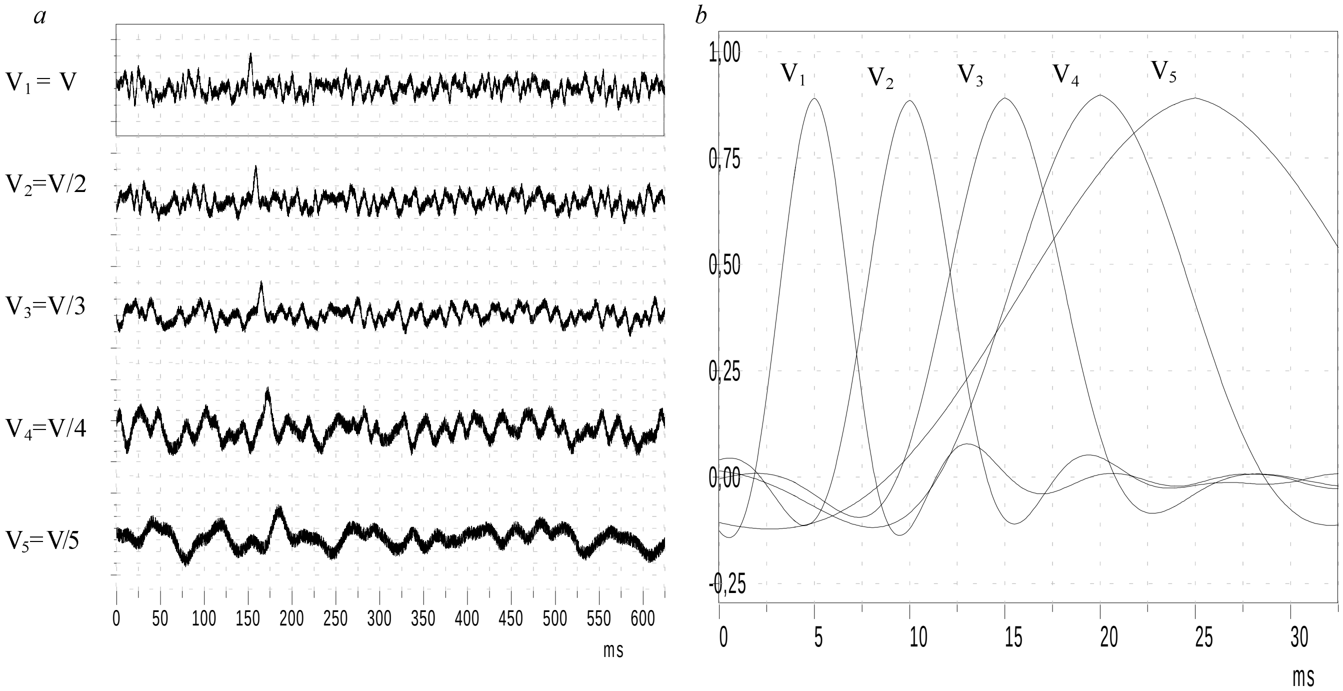


Fig. 4. Time patterns (a) and normalised cross-correlation functions (b) of signals modelled according to formula (2) for different values of V *with distance between sensors assumed constant and* $\sigma_z/\sigma_x = 0.5$

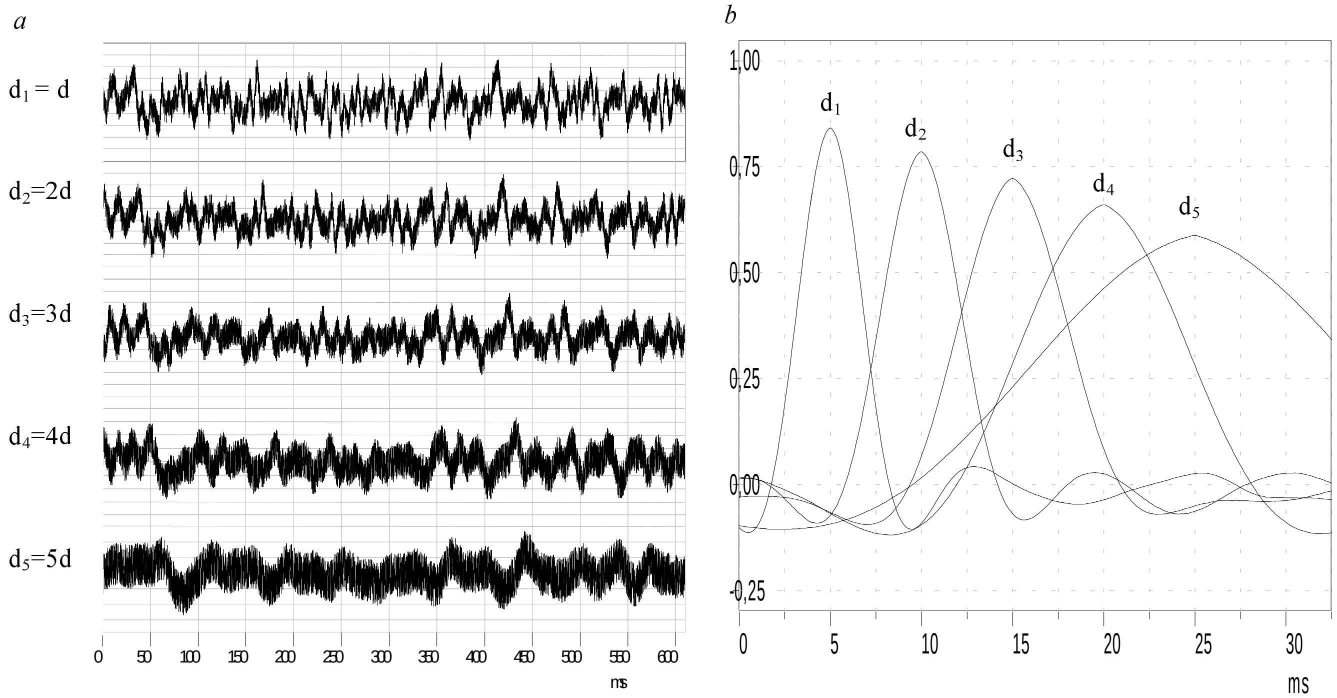


Fig. 5. Time patterns (a) and cross-correlation functions (b) for signals modelled according to relation (1) for different distances d and for linear function $f_l(l)$

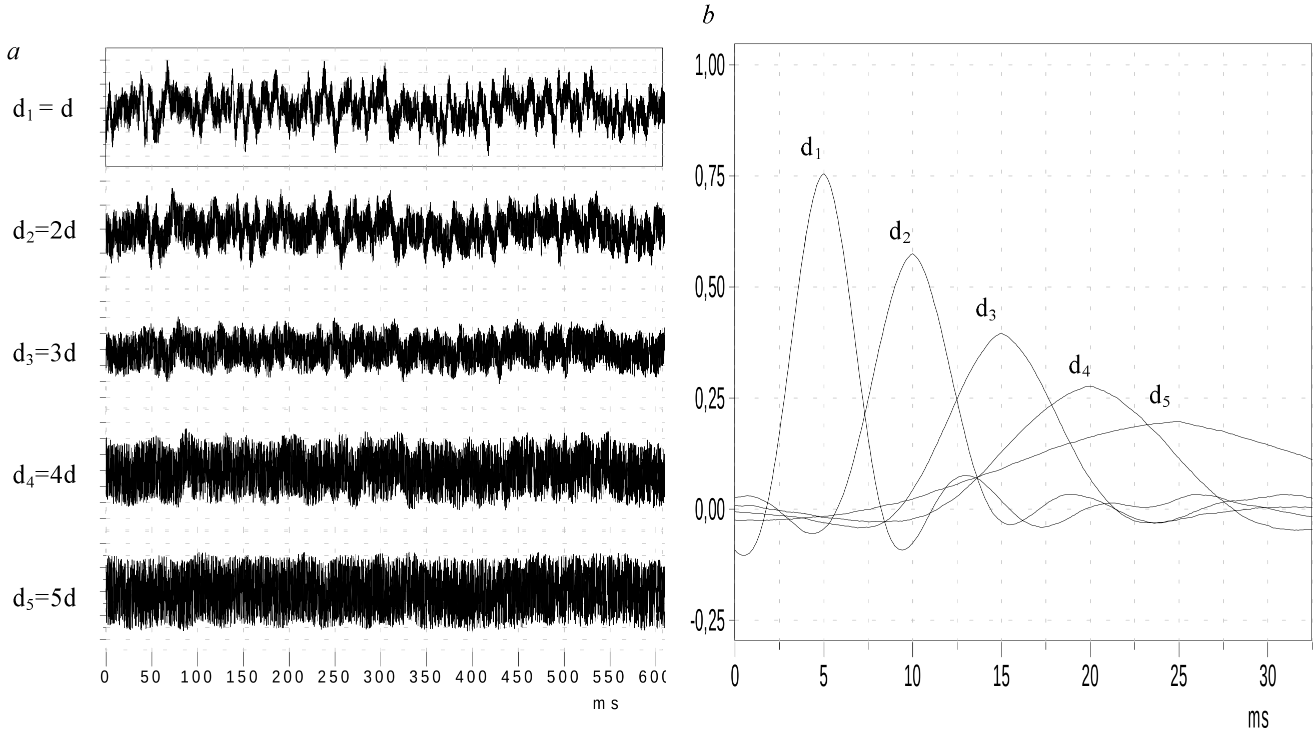


Fig. 6. Time patterns (a) and cross-correlation functions (b) for signals modelled according to relation (1) for different distances d *and for function* $f_l(l)$ *of exponential type*

Required changes in correlation function amplitude have been obtained, just like in the former case, by means of shaping of the spectrum and proper selection of model parameters (3). The values of the ratio $\sigma_x/[f_l(l_0)\sigma_z]$ adopted for delays of 5, 10, 15, 20, and 25 ms, were 1.17, 0.71, 0.45, 0.29, and 0.22, respectively. The pattern of changes in cross-correlation function main extreme amplitude presented in Fig. 6b corresponds to patterns of this functions obtained in measurements of parameters of water flow in pipelines performed by means of ultrasonic sensors at different distances *d*, which were multiples of the pipeline diameter [1, 17].

3. Summary

- Modelling of signals obtained from sensors in statistical measurements of transport parameters of rigid solid bodies (metal sheets, bars, strips) requires taking into account small disturbances of the delayed signal and shaping spectra of the modelled signals accordingly to variations in velocity of the object.
- Measurements of transport parameters of media such as powders, granulates, one- and multi-phase liquids etc. by means of statistical methods represent more complex problem than analogous measurements of rigid solid bodies. In this case, the signals obtained from sensors are characterised with exceptionally unfavourable signal-to-noise ratio, which has to be taken into account in creation of models of such signals.
- In the set-up described in this paper, parameters of the modelled signals can be easily selected in order to obtain patterns corresponding to real signals obtained in specific measurement conditions and for specific medium type. The presented signal models can be used in simulation examinations of statistical measurement methods of transport parameters and in other applications which make use of mutually delayed stochastic signals.
- The advantage of application of measurement set-up controlling software packages (e.g. DASYLab) consists in possibility of using them for both modelling of signals and for simplified realisation of real measurement set-ups, e.g. by means of classical measurement devices or DAQ computer boards co-operating with proper transducers.

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УДК 536.53

КОНТРОЛЬ ТЕМПЕРАТУРИ ПРИ ОЦІНЮВАННІ ЯКОСТІ ГОТЕЛЬНИХ ПОСЛУГ

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Державний науково-дослідний інститут “Система”, вул. Кривоноса, 6, 79008, Львів, Україна

Проаналізовано сучасний стан проблеми контролю температури під час надання та оцінювання якості готельних та туристичних послуг. Запропоновано структуру та експериментально досліджено макет цифрового термометра з напівпровідниковими сенсорами.

Проанализировано современное состояние проблемы контроля температуры и оценки качества при гостиничном и туристическом обслуживании. Предложена структура и экспериментально исследован макет цифрового термометра с чувствительными полупроводниковыми сенсорами.

The up-to-day conditions of temperature check and quality estimation at the hotel and tourism service are analyzed in this paper. The new measurement current modulation method and thermometer scheme for unification of p-n junction sensor are proposed. The experimental investigations of semiconductor digital thermometer are made.

Вступ. Самопочуття та відчуття комфортності людини значною мірою залежить від зміни параметрів довкілля та житлово-побутових умов. Нормативні документи встановлюють певні вимоги щодо кліматичних та житлово-побутових умов при наданні готельних та туристичних послуг [1, 2]. Це насамперед температура, вологість та тиск повітря довкілля і залежно від класу готелю, значення температури гарячої води, в приміщенні в опалювальний сезон, підігрівної підлоги у ванній кімнаті тощо.

Однак перелік та якість наданих готельних та туристичних послуг повинні постійно розширюватись та вдосконалюватись для чіткого визначення потреб споживача, уникнення незадоволеності споживача при оптимізації витрат на забезпечення належного їх рівня [3,4]. Окрім того, постачальник послуг повинен періодично і систематично перевіряти якість вимірювання, щоб гарантувати її подальше ефективне використання [5]. Вітчизняна промисловість не випускає недорогі вимірювальні засоби для контролю параметрів довкілля.

Тому безперервний контроль одного із найважливіших параметрів кліматичних та житлово-побутових умов температури є актуальним завданням.