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Accuracy of cross correlation velocity measurements in two-phase gas–solid flows ☆

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A B S T R A C T

The paper presents a detailed discussion of the errors of quantisation and sampling (conversion) caused by A/D converters and brought up for discussion on the basis of some original formulae derived. These converters are implemented in analogue–digital parts of measuring systems designed and produced to be in operation according to the cross correlation method of measurement of mean flow velocity of solid particles especially in pipelines of pneumatic transport. The discussion is based on an analysis of a real measuring system in which electrostatic flow probes were used to detect the smallest changes in charge carried by solid particles in pipes of pneumatic transport and in the air during their two-phase gas–solid flows. In the cross correlation of signals induced in electrostatic flow probes a non-intrusive electrostatic method is employed which is based on the phenomenon of electrostatic induction brought about by the time-varying charge of particulates in conveying pipes or by the so-called electrostatic flow noise. The conclusion of the discussion can be spread among other kinds of cross correlation method including the capacitive or electromagnetic methods based on the types of sensors named after the names of the methods. Certain excerpts in the paper are taken from or based in part on some passages from the author's monograph (Gajewski, 2010 [1]).

1. Introduction

The cross correlation method of measurement of the mean flow velocity of particulates in the two-phase gas–solid flows in pipes of pneumatic transport or in the air is a very useful tool in the metrology at all and especially in the non-contact, non-intrusive measurements of the mean flow velocity. The method is relatively insensitive to any spurious external signals which are strongly rejected because of no correlation with the input signals of probes, sensors, or transducers used. The cross correlation of those interferences tends to zero on condition that the sampling (or integration) time of useful input signals is sufficiently long. This is the most vital advantage of the cross correlation method of measurement of the mean flow velocity of solids [2].

There are some non-contact methods for measuring the parameters of two-phase pipe flows in pipelines without any disturbance to the parameters being measured and to the flow itself. One of them is a non-intrusive electrostatic method based on the phenomenon of electrostatic induction [3–8] and which permits one to measure the electric charge carried on travelling solid particles, the mass flow rate or solids volume loading of those particles. With the use of two electrostatic flow probes the mean flow velocity of those particles can also be measured on the basis of the cross correlation.

The electrostatic flow probes are used in the non-intrusive electrostatic method which were widely described elsewhere [3–9]. They are metal full-ring shaped electrodes and mounted on the fragment of a dielectric pipe put in a special measuring head. Two such probes are separated from each other by a certain distance that is precisely fixed. In other non-intrusive methods other types of sensors, e.g. capacitive, electromagnetic sensors, are used which also do not disturb the flow of particulates and can be used in the cross correlation method for measuring the mean flow velocity [10]. The probes detect the so-called *electrostatic flow noise* as generated by the flow of charged solid particles. The detection is based on the non-intrusive electrostatic method in which electric charge carried by solid particles induces charge and potential on the probes. The charge induced causes electric current to flow between the probe(s) and the earth through the specially designed processing electronics when the system impedance is relatively small and the system tends to differentiate the so obtained signals of the probes. When the system's input impedance is extremely high then the measuring system

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☆ The author decided to disseminate the information contained in this paper among a wider group of readers for their benefit though its part is the material presented in the monograph "Electrostatic induction in two-phase gas–solid flow measurements. 50 years of a measurement method" [1]). Certain fragments both in the monograph and in the paper were published earlier in several author's papers.

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transfers the input signals (potentials of the probes) proportionally without loading the probes as the sources of useful signals [11,12]. The signals produced at the outputs of both probes are stochastic (stationary and ergodic) ones and are induced in the probes by the electrostatic flow noise.

It is crucial that the accuracy of the measurement be as high as possible. There are some errors and uncertainties caused by a measuring system in itself. These occur in the analogue part and the analogue–digital part of a measuring system and especially in its processing electronics.

The errors in the analogue part are related to a distance between the probes — the separation (spacing) of the probes — that must be determined precisely to obtain a sharp peak of the cross correlation function. This in turn results in the transit time determined exactly and the mean flow velocity is then calculated correctly. The considerations are valid for the fully developed turbulent two-phase gas–solid flows when the flow velocity profile over the cross-section of a pipe is uniform and on the assumption that a frozen flow pattern, that is any flow disturbance travels between the probes with the velocity that is somewhat lower than that of a gas carrier (the slip velocity between solid particles and fluid) and without any distortion.

Here, the primary goal of this paper is to show the discussion of some errors that are related to the analogue-to-digital conversion of analogue input signals of two electrostatic flow probes before the digital output signals are cross correlated to permit one to determine the mean flow velocity. The errors are primarily made in and by A/D converters, and are discussed below.

2. Optimum probe spacing determination

It is assumed that the electrostatic flow probe (or another similar type of sensor) and a preamplifier in any microprocessor-based system are assembled correctly and the separation (spacing) of the probes is optimum and fit precisely according to the formula derived by Mesch and Kipphan [13]:

$$L_{\mathrm{opt}} = 0.88\frac{\upsilon^2}{\sigma_{\mathrm{v}}\omega_0}, \tag{1}$$

where σ_{v} is the standard deviation of the flow velocity υ and ω_0 ($= 2\pi f_{\mathrm{c}}$) is the upper cut-off angular frequency of the corresponding power density spectrum — bandwidth of the electrostatic flow noise. Then the solids mean flow velocity υ is easily calculated from

$$\upsilon = \frac{L_{\mathrm{opt}}}{\tau_0}, \tag{2}$$

where τ_0 is the transit time that is the time required for solid particles (a frozen pattern) to travel downstream between two electrostatic flow probes separated by L_{opt}. The transit time τ_0 is determined from the maximum of the cross correlation function $R_{\mathrm{xy}}(\tau)$:

$$R_{\mathrm{xy}}(\tau) = \lim_{T\to\infty}\frac{1}{T}\int_0^T x(t-\tau)y(t)\,\mathrm{d}t = \lim_{T\to\infty}\frac{1}{T}\int_0^T x(t)y(t+\tau)\,\mathrm{d}t, \tag{3}$$

where $x(t)$ and $y(t)$ are analogue stochastic input signals of two electrostatic flow probes; τ is the cross correlation lag (time delay), and T is the sampling (integration) time. The cross correlation function $R_{\mathrm{xy}}(\tau)$ reaches its maximum when the cross correlation lag τ is equal to the transit time τ_0 of the tagging signals.

An analysis of the signal bandwidth of a single probe and processing electronics (preamplifiers and other parts, e.g. A/D converters) is based on the *Fourier* transform of the probe's output signal (e.g. potential, voltage, current, etc.) and gives explicitly the frequency band of the signal in the form [13,14,15]:

$$\omega_{\mathrm{uc}} \equiv \omega_0 = 2\pi\frac{\upsilon}{b}, \tag{4}$$

where ω_{uc} is the frequency band and upper cut-off angular frequency and b is the width of the probe. The bandwidth is obtained as the first zero of a modulus of the frequency response function.

By introducing Eq. (4) into Eq. (1) one obtains

$$L_{\mathrm{opt}} \simeq 0.14\frac{\upsilon}{\sigma_{\mathrm{v}}}b. \tag{5}$$

The optimum spacing (separation) of two probes can be found experimentally. This way seems more effective and exact than that based on the calculation using Eqs. (1) or (5). The correlation coefficient $\rho_{\mathrm{xy}}(\tau)$ (coherence of the signals of both probes) is a useful tool to determine the optimum correlated distance L_{opt} between the probes. It is a good optimization criterion that strongly depends on the distance L between the probes. For the mean flow velocity υ precisely fixed that is when the distance between the probes is a correlated one L_{opt} the correlation coefficient always reaches its maximum. Moreover, when the flow velocity increases, so does L_{opt}, as both Eqs. (1) and (5) show. Therefore the correlation coefficient $\rho_{\mathrm{xy}}(\tau)$ should be used to properly estimate or determine the correlated distance L_{opt} and which is defined as follows [14]:

$$\rho_{\mathrm{xy}}(\tau) = \frac{R_{\mathrm{xy}}(\tau)}{\left[R_{\mathrm{x}}(0)R_{\mathrm{y}}(0)\right]^{0.5}}, \tag{6}$$

where $R_{\mathrm{x}}(0)$ and $R_{\mathrm{y}}(0)$ are the autocorrelation functions of the $x(t)$ and $y(t)$ signals of both probes, respectively, for the argument $\tau_0 = 0$. When $|\rho_{\mathrm{xy}}(\tau)| \to 1$ or attains a maximum (minimum) value in a set of the $\rho_{\mathrm{xy}}(\tau)$ values for given spacing between the probes, then the corresponding spacing is just a proper one — the correlated distance L_{opt}. Eq. (2) also applies in this case.

A fragment of an experimental installation of the pneumatic transport used is shown in a simplified form in Fig. 1; there are presented only the cross-sections of a measuring head and some fragments of a pipeline. (The full description of the installation can be found, e.g., in [16].) The measuring head provides mechanical support and electromagnetic screening to protect the input of a measuring system against spurious electromagnetic interferences and is earthed. (The probes in themselves are the sources of

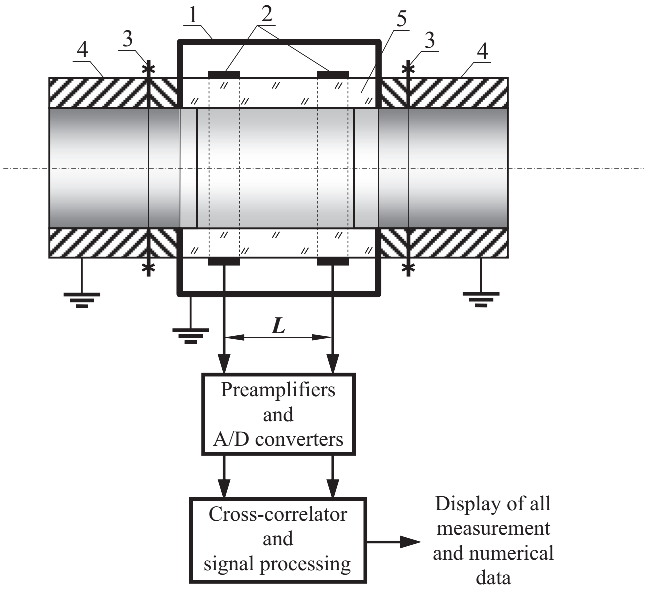

Fig. 1. Schematic of a fragment of the experimental pneumatic transport installation: a measuring head and pipes. Description in the text.