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APPLICATION OF HILBERT TRANSFORM TO SIGNAL PROCESSING IN RADIOISOTOPE MEASUREMENTS OF THE LIQUID – SOLID PARTICLES FLOW IN THE VERTICAL PIPELINE

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Abstract – The paper presents application of the gamma-absorption method to a solid particles hydrotransport evaluation in a pipeline. The flow of the mixture was examined by a set of ^{241}Am sources and NaI(Tl) probes. For analysis of the stochastic signals provided by detectors the cross-correlation function with the Hilbert Transform of delayed signal (CCFHT) have been applied. The experiments showed that the combined uncertainty of the average velocity of solid particles did not exceed 0.01%.

Keywords: two-phase flow, gamma ray absorption, stochastic signals, cross-correlation, Hilbert Transform.

1. INTRODUCTION

Two-phase flows frequently occur in environment and technology. In mineral industry, e.g., in the mining, a pipeline transportation is using the following two-phase flows: liquid – gas, liquid – solid phase, liquid I – liquid II or gas – solid phase. A typical example would be vertical pipeline hydrotransport of minerals, e.g., polymetallic nodules from sea bed. Nodules are porous organic and mineral compositions which contain various metals (mostly Mn, Si, Fe, Al, Na, Mg, Ni, K, Cu). The ocean nodules usually have the form of irregular grains with the diameter of several up to 0.5 m and density of about 2 g/cm^3 in wet state. The mining of nodules using the hydraulic method requires grain vertical transportation by water to sea level in the extremely hard and varying environment. For determination of the transportation parameters of nodules we propose to apply an advanced non-invasive measurement method, employing radionuclide techniques [1-5] and statistical analysis of obtained random signals. Because these signals, after proper pre-processing, may be ergodic and Gaussian, such classical methods in both time and frequency domain as the cross-correlation function (CCF) and the phase of cross-spectral density may be applied [1, 4-10]. Recently also other methods of the time delay estimation, e.g., differential and combined [6, 10, 11] or the one based on conditional averaging [12, 13] have been tested.

In this work we present the cross-correlation with Hilbert Transform of delayed signal (CCFHT) applied to liquid – solid phase flow investigation in a vertical pipeline. In the experiment described as solid phase the ceramic models representing natural polymetallic ocean nodules were used. The results of time delay and average velocity estimation as well as their standard uncertainties received by use CCFHT method have been compared with the corresponding classical cross-correlation results.

2. GAMMA ABSORPTION METHOD

Two-phase flow measurements utilizing radioactive isotopes have been used for more than 100 years now. The absorption method based on photons beam emitted by a closed gamma-ray source through a mixture flowing in a pipeline [2-7] is relatively safe for a staff. The idea of the gamma absorption method applied to the liquid - solid particles flow in a vertical pipeline is presented in Fig. 1.

Two sealed radioactive sources (1) emitting gamma radiation beams were shaped by the collimator (2). Due to that, photons could pass through the pipeline with the analysed mixture. As a result, the changes of the radiation intensity might be recorded by scintillation probes (3) mounted in collimators (4) and then converted into output electrical impulses [14, 15]. The above mentioned points allow us to assume that observed count rates I_x and I_y at the outputs of probes depend on condition of the flowing medium in the selected cross section. As a consequence, determination of velocity of the minority phase is based on measuring the time delay τ_0 of signals received from two detectors placed at known distances L to each other [4-7, 10, 11].

The measuring principle presented in Fig. 1 was applied in the experimental laboratory stand for investigation of the polymetallic nodules hydrotransport, built up in the Hydraulic Laboratory of the Wroclaw University of

Environmental and Life Sciences (Poland). The laboratory installation was described in detail in [6].

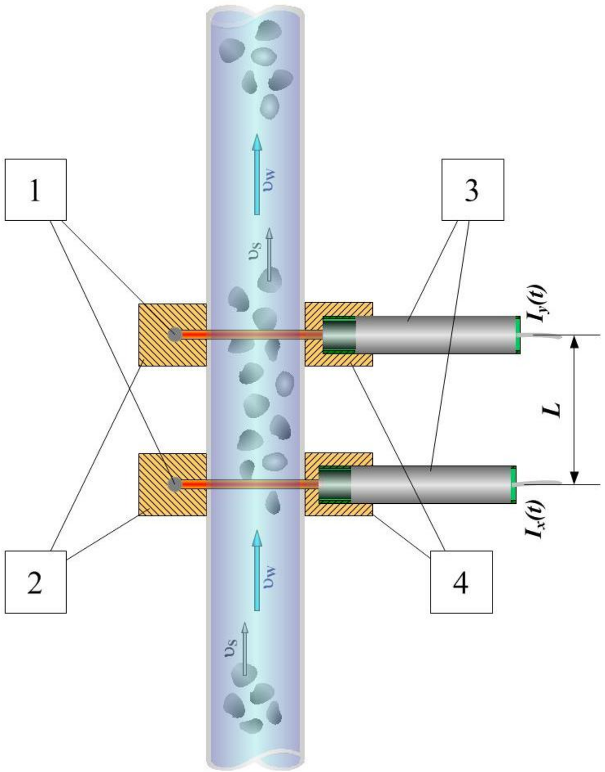

Fig. 1. The principle of the gamma absorption measurement of liquid - solid particles flow in pipeline: 1 – sealed radioactive source, 2 – collimator of the source, 3 – scintillation probe, 4 - collimator of the detector, υ_s – velocity of solid particles, υ_w – velocity of water.

The basic part of the ducting is a vertical acrylic glass pipeline of the 7.75 m length with the 150 mm internal diameter. The view of the measuring section of the pipeline with flowing mixture is shown in Fig. 2.

Fig. 2. A part of the pipe with the flowing mixture.

In the presented investigations two linear ^{241}Am γ-ray sources with an activity of 100 mCi and two probes with 2” NaI(Tl) scintillation crystal dislocated at the distance of L = 90 mm were used. The data acquisition equipment was comprised of the dedicated EC Electronics counter HSC 8000 connected to PC using an USB port.

3. SIGNAL ANALYSIS

Voltage pulses I_x and I_y counted within the selected sampling time Δt create mutually delayed stochastic signals $x(t)$ and $y(t)$. The time records of signals obtained in the WRS012 experiment (after centering and filtration in order to remove a noise and radiation background contribution) are presented in Fig. 3. In this experiment the number of data N = 300000, and Δt = 1 ms.

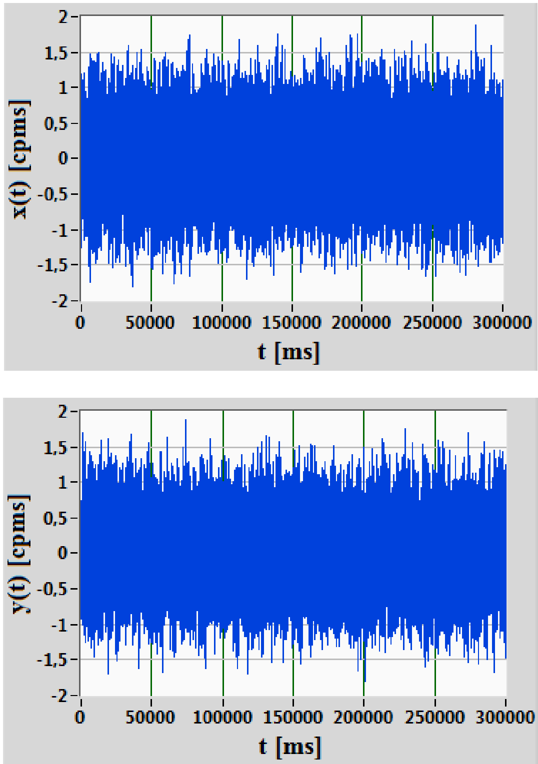

Fig. 3. The time records of signal $x(t)$ and $y(t)$ (after preprocessing) in the WRS012 experiment.

The mean axial velocity of the solid particles υ_s is determined from the dependence:

$$\upsilon_s = L / \tau_0 \,, \tag{1}$$

where τ_0 – transportation time delay.

The frequently used method of τ_0 estimation of the ergodic random signals $x(t)$ and $y(t)$ is based on CCF $R_{xy}(\tau)$ defined by equation:

$$R_{xy}(\tau) = \lim_{T \to \infty} \frac{1}{T} \int_0^T x(t) \cdot y(t+\tau) dt \,, \tag{2}$$

where T is the averaging time, τ – time delay [1, 8].

The τ_0 transportation time delay is determined based on the CCF maximum position.

In this work we have studied the application of the CCFHT method defined as follows [16]:

$$\tilde{R}_{xy}(\tau) = \lim_{T\to\infty} \frac{1}{T}\int_0^T x(t)\ \tilde{y}(t+\tau)dt\,, \tag{3}$$

where $\tilde{y}(t)$ is Hilbert Transform of signal $y(t)$:

$$\tilde{y}(t) = H[y(t)] = \frac{1}{\pi}\int_{-\infty}^{\infty} \frac{y(u)}{(t-u)} du\,. \tag{4}$$

In this method, the time delay τ_0 is determined by finding a zero crossing of CCFHT function.
The analyses and simulations described in [16-18] revealed that the CCFHT has a lower standard deviation of time delay τ_0 than CCF in case of non-correlated samples of low-pass random signals for medium and high values of signal-to-noise ratio.

4. EXEMPLARY RESULTS

The exemplary plots of the CCF and CCFHT obtained in the WRS012 experiment are shown in Fig. 4.

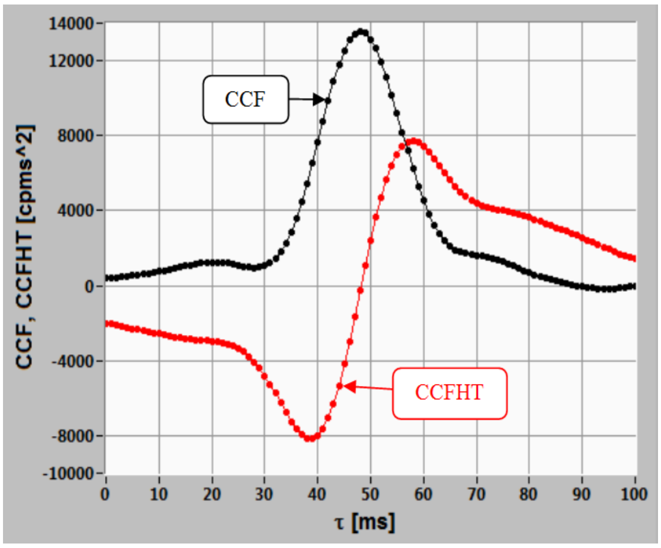

Fig. 4. CCF and CCFHT obtained in the WRS012 experiment.

In the CCF method determination of τ_0 is based on the location of the maximum value position. For this purpose selected range of data around the maximum of the CCF have been interpolated with the Gaussian probability density distribution $p(\tau)$:

$$p(\tau) = p_0 + \frac{1}{\sigma\cdot\sqrt{2\pi}}\exp\left(-\frac{(\tau-\hat{\tau}_0)^2}{2\cdot\sigma^2}\right), \tag{5}$$

where: p_0 – normalization level of the Gauss function, σ – standard deviation of the fitted distribution.

Therefore the $\hat{\tau}_0$ estimator of the mean transportation time delay is obtained as the first moment of this distribution [8, 12] and the standard uncertainty $u(\hat{\tau}_0)$ is given by:

$$u(\hat{\tau}_0) = \sigma/\sqrt{q}\,, \tag{6}$$

where q – number of points selected for the interpolation.

To calculate the transportation time delay based on CCFHT, we used the simple linear regression i.e. $y = a_0 + a_1\tau$. For $\tau = \tau_0$ it is true that $y = 0$ so one can obtain $\hat{\tau}_0 = -a_0/a_1$.

In this case the standard uncertainty of time delay $u(\hat{\tau}_0)$ can be calculated from the formula [19]:

$$u(\hat{\tau}_0) = \left[\frac{\sum_{i=1}^{m}\left(a_0 + a_1\tau_i - \tilde{R}_{xyi}\right)^2}{m(m-2)a_1^2}\right]^{1/2}, \tag{7}$$

where m is a number of points used in the interpolation procedure.

The results of the time delay estimation using CCFHT method and its standard uncertainty obtained in the WRS012 experiment for $m = 11$ are presented in Table 1. The similar results obtained under analysis of the CCF distribution for $q = 29$ are given for comparison.

The mean axial velocity of the solid particles υ_s was calculated from equation (1). The combined standard uncertainty $u_c(\upsilon_s)$, with negligible small uncertainties of the acquisition set, depends on inaccuracy of uncorrelated L and $\hat{\tau}_0$ determination:

$$u_c(\upsilon_s) = \left[\left(\frac{\partial\upsilon_s}{\partial L}\right)^2\cdot u^2(L) + \left(\frac{\partial\upsilon_s}{\partial\hat{\tau}_0}\right)^2\cdot u^2(\hat{\tau}_0)\right]^{1/2}, \tag{8}$$

where $u(L)$ is the standard uncertainty of the L distance between detectors.

Table 1. Results of the time delay estimation in the WRS012 experiment.

Method	Time delay $\hat{\tau}_0$ (ms)	Standard uncertainty $u(\hat{\tau}_0)$ (ms)
CCFHT	48.30	<0.01
CCF	48.23	1.37

Results of the average velocity υ_s and its combined uncertainty $u_c(\upsilon_s)$ [20] obtained in the WRS012 experiment by use CCFHT and CCF methods are presented in Table 2.

Table 2. Average velocity of air υ_s and its uncertainty $u_c(\upsilon_s)$.

Method	Average velocity υ_s (m/s)	Combined uncertainty $u_c(\upsilon_s)$ (m/s)
CCFHT	1.863	<0.001
CCF	1.866	0.053

5. CONCLUSIONS

Based on the carried out research and preliminary results, it can be stated that the CCFHT method may be successfully applied to such complex measurement as nodules vertical pipeline hydrotransport evaluation by the radioisotope techniques.

Moreover it was found that the combined uncertainty of the average velocity of solid particles in the exemplary WRS012 experiment did not exceed 0.01% for CCFHT (in comparison with 2.84% for CCF) which is a satisfactory result in research and numerous industrial applications.

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