

Monitoring of coal jig operation using a radiometric meter with a variable time of measurement

S Cierpisz¹ and J Joostberens²

¹Institute of Innovative Technologies EMAG, Leopolda 31, 40-189 Katowice, Poland

²Silesian University of Technology, Faculty of Mining and Geology, Akademicka 2, 44-100 Gliwice, Poland

jaroslaw.joostberens@polsl.pl

Abstract. Authors discuss the problem of how to monitor the coal/water pulsating bed in a jig with the use of a radiation density meter. Time of measurement applied in radiation monitors is usually constant in industrial radiometric monitors. The dynamic error in the process of measuring changes in density depends on the time of measurement; its optimal value can be found for a given shape of density changes. Authors propose an alternative method of signal filtration for variable time of measurement during a cycle of pulsations. Good results can be achieved for a linear relation between the time of measurement and time derivative of the density. The time derivative of the density can be determined for a long period of time on the basis of industrial tests which establish average changes in density in subsequent cycles of pulsations. In this case, the dynamic error of measurement MSE can be reduced by half compared to the optimal constant time of the measurement.

1. Introduction

Raw coal is often beneficiated in gravitational processes, where coal grains are stratified according to their densities in a pulsating coal/water medium in jigs, as shown in figure 1. This problem was discussed in [1-6].



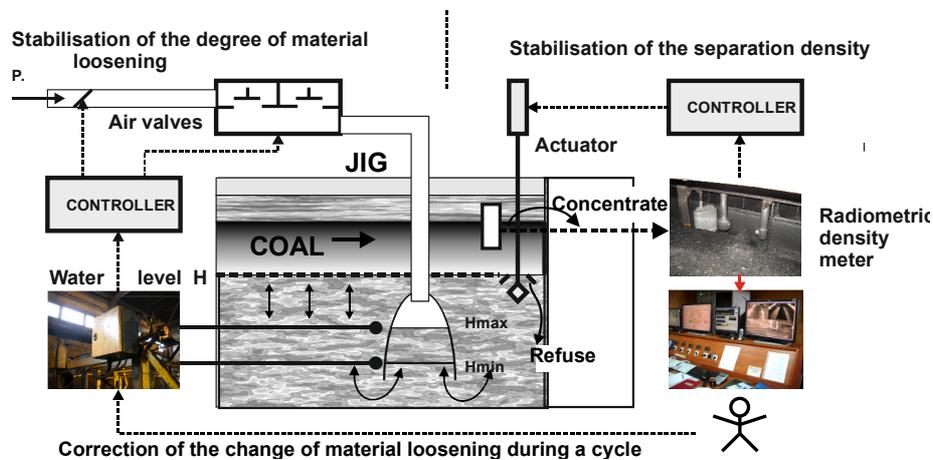


Figure 1. Control system of a coal separation process with a radiometric monitor of a separation density.

Separation of stratified material is based on a chosen separation density which is the density of the layer reporting in half to the upper product (concentrate) and in half to the discharged lower product (refuse). The refuse is removed through the discharge gate and the concentrate overflows the splitting gate. The quality of products is determined by the density of the separation layer. Its position should be monitored on-line and kept at the splitting-gate level regardless of the changes in the tonnage of the feed or changes in the washability characteristics of the raw coal. It is usually measured by a metal float of required shape and density.

The desired position of a float is stabilized through controlling the amount of the lower product discharged through the bottom gate. Float is not accurate in indicating the chosen density layer, especially with changes in the amount of the feed and varying composition of the grains. In new experimental systems, floats are being replaced by more accurate radiometric density meters which can monitor the process of material loosening/compressing during each cycle of coal/water pulsations. The output signal from a radiometric meter can be used for two purposes:

- to stabilize the shape of dynamic changes in density;
- to stabilize the separation density measured when material is compressed at the end of the cycle.

The typical dynamic change in coal/water density in a single cycle of separation process is shown in figure 2.

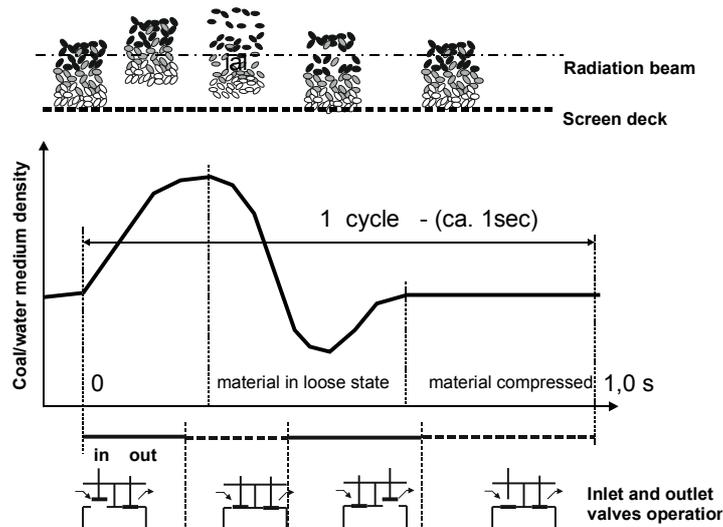


Figure.2. Changes in medium density in a single cycle of pulsations.

At first, while the inlet air valve is open, the material is lifted upwards without loosening the upper part of the coal bed. Then the material gradually separates, the inlet valve is closed and grains sink again to be consolidated at the end of the cycle. The outlet air valve is opened to speed-up the sinking. Then the outlet valve is closed to ensure the same hydraulic conditions for the next cycle.

The shape of changes in density at the level where the concentrate overflows the upper discharge gate varies due to variations in the feed tonnage, density composition of the grains and fluctuations in air pressure in the air collector. To achieve the best conditions for coal separation, i.e. the optimal stratification of grains according to their density and constant separation density in the jig, the shape of changes in density during each cycle of pulsations should be stabilized. The radiometric density monitor should reproduce changes in medium density with minimum error to achieve the best monitoring and control results.

The measuring head of a radiometric density meter consists of a radiation source (^{60}Co , ^{137}Cs) and a detector which usually is a scintillation counter. The review of detectors was presented in [7]. The output signal from the detector is always a discrete stochastic signal (Poisson distribution), regardless of the character of the input signal (i.e. density) modulating the intensity of the detected radiation beam. The longer the averaging time, the higher the statistical (static) accuracy of the monitor. At the same time, if the input signal varies, the dynamic error of the measurement is higher. This suggests that for a given shape of the input signal and a given structure of the monitor circuit, one can find an optimal averaging time of input pulses, which allows for the minimum dynamic error within accepted criteria. Furthermore, this leads to the application of a circuit with an adapting time of input pulses averaging. This problem was discussed in [8, 9]. If the input signal is, for example, a step function and the density monitor is to reproduce this change, the time of measurement should be small at the beginning of the measurement in order to speed-up the reaction of the meter and then it should increase in order for the new value of the density to be read out accurately. In the case of stochastic changes in the measured density, the signal from the detector is a doubly non-stationary Poisson process. Such processes were discussed in [10,11,12].

The problem becomes important when changes in density are frequent and rapid; if this is the case, the process requires short times of measurements. It may happen in technological systems for coal separation in a jig where stratification of coal grains based on their densities is performed in a pulsating coal/water bed to produce two or three final products: concentrate and refuse or middlings.

Radiometric density meters in which time of measurement adapts to changes in measured densities require instantaneous monitoring of these changes over short periods of time. Due to the stochastic nature of the signal coming from the radiation detector, it is difficult to determine the derivative of the

density signal as a function of time without significant errors. Also, software applied to measure the changes in density in order to adjust the period of time for the next measurement must be efficient enough to operate on-line in short periods of time (i.e. 1-2 ms). The aim of this paper is to propose an alternative method to adjust the time of measurement on-line. This method is based on an a priori determination of the change in time of measurement on the basis of the average shape of changes in density in subsequent cycles of the coal bed pulsations.

2. The method of signal filtration from the digital radiometric meter

The output signal $s(t)$ from the scintillation detector can be processed in an analogue integrator or as a moving average number of pulses $u(t)$ counted during the time of measurement t_s as it is shown in figure 3. The relation between the measured medium density $\rho(t)$ and the mean intensity of registered pulses $n(t)$ is theoretically exponential but for small changes of density can be approximated by a linear equation. The value of the signal u at the output of the density meter at j -th period of time of measurement t_s is determined from the following equations:

$$u[i] = \frac{1}{k_n} \cdot \left(n_0 - \frac{1}{t_s} \cdot k[i] \right) \quad (1a)$$

$$k[i] = \sum_{l=1}^{t_s/\Delta t} S \left[\frac{t_s}{\Delta t} - l \right] \quad (1b)$$

k_n – coefficient,

n_0 – intensity of pulses for the reference density (e.g. water),

S – number of pulses (0 or 1) in the elementary period of time,

Δt – elementary period of time (determined by the dead time of the radiation detector) $\Delta t < t_s$.

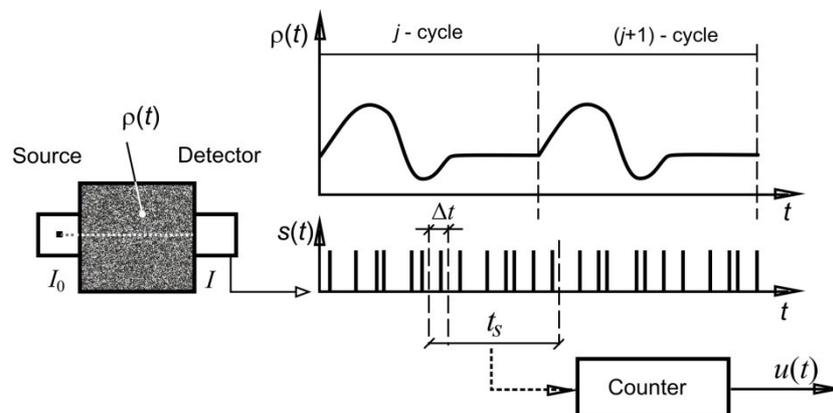


Figure 3. Digital filtration of stochastic signal from the detector.

Extending the measurement time t_s reduces the statistical error of the measurement but at the same time deteriorates the dynamic properties of the density meter. On the other hand, the short measurement times improve the dynamic properties of the meter, but increase stochastic fluctuations in the signal $u(i)$. An example of simulated changes in the signal $u(i)$ as a response to changes in the bed density in a jig for short and long measurement time t_s is shown in figure 4.

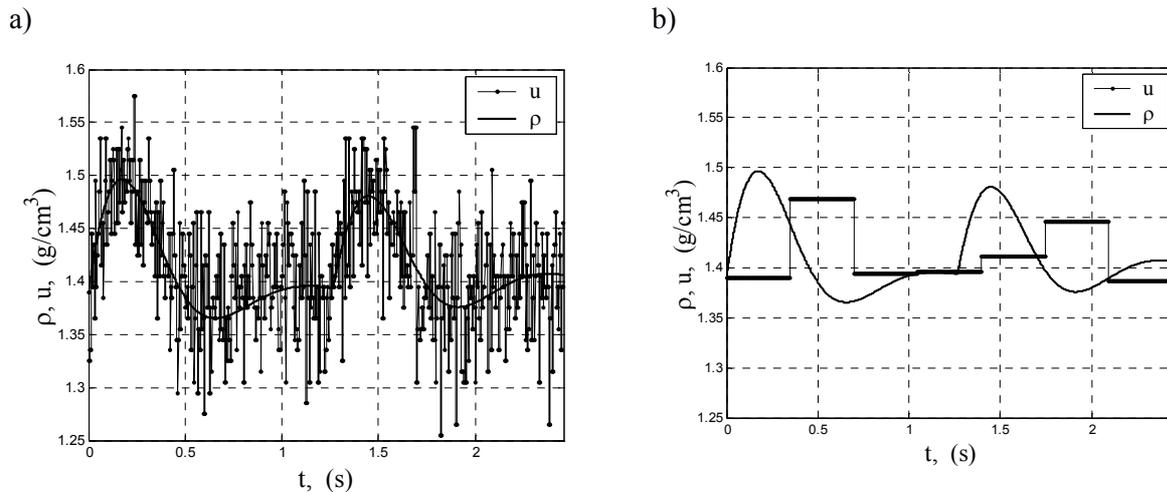


Figure 4. Changes in the measured density signal $\rho(t)$ and changes in the output signal $u(t)$ for (a) short and (b) long measurement time t_s .

The time of measurement t_s is constant in typical industrial radiometric monitoring systems. The problem of determining its specific value lies in a compromise between the expected static accuracy of the meter and the dynamic error caused by inertia resulting from the measurement time t_s . This problem is especially important in monitoring fast changes in the density of the coal/water bed in a jig. Reproducing a rapid change in density requires a short time of measurement, which makes it more difficult to measure the instantaneous density value accurately. The optimal time of measurement t_s , for a known change in the media density $\rho(t)$, can be determined from the minimum value of the mean square error:

$$\text{MSE}_c = \frac{1}{N_i} \sum_{m=1}^{N_i} (u[i] - \rho[i])^2 \quad (2)$$

N_i – number of data used for calculation of t_s .

As mentioned earlier, better results of the dynamic measurement of the bed density in a jig may be expected when the time of the measurement t_s depends on the speed of changes in density.

For example, in the case of a step change in density, the time of measurement at the beginning should be short to speed-up the reaction of the meter and then should increase for a more accurate read-out of the density value in the steady state. Radiometric monitors with times of measurement adapting to changes in the measured signal were discussed in [8]. The discussed systems applied a differential filter to detect a change in a previously smoothed signal and to use it to immediately adjust the share of signals from three filters with different times of measurement (fast, medium, long) in the output signal $u(t)$. These adaptive filters give better results than filters with the constant time of measurement t_s determined by the criterion (2). The main problem in this case lies in the accuracy of determination of the change (derivative) in density as the signal from the radiation detector is the stochastic series of pulses whose mean intensity is modulated by the measured density. The advantage of the adaptive method lies in the possibility of applying it to any shape of change in the measured density. The disadvantage, in the case of radiometric meters, lies in (a) significant noise in the differential signal and (b) the short time required for the execution of the algorithm to process the signal and predict the time of measurement t_s for the subsequent step.

In this paper we propose another method to filter the signal from the radiation detector which can be used for monitoring special signals similar to periodic changes in the density of the coal/water bed in a jig. A typical shape of a change in bed density in a jig is shown in figure 3 and figure 4. This change is repeated in the subsequent cycles of bed pulsation. Depending on conditions, changes in density may differ in absolute values of ordinates but their character remains similar from cycle to cycle. The mean ("typical") change in density can be presented by a function of time and this function

can be further used to adjust subsequent times of measurement t_s according to the accepted function. This concept of the density signal processing is expected to give smaller dynamic errors of measurement in comparison to the method with the constant time of the measurement; in some cases it may give better results than adaptive algorithms. In this paper we limit our analysis to the determination of optimal parameters to process a "typical" periodic signal of changes in the bed density in a jig.

Mathematical models of changes in coal/water bed density, based on experimental data from two coal mines, were presented by in [9]. A typical change in density can be described by equation (3):

$$\rho(t) = A_j \cdot e^{-\alpha_j \cdot t} \cdot \sin(\omega_j t - \psi_j) + \rho_{uj} \quad (3)$$

$A_j, \alpha_j, \omega_j, \psi_j, \rho_{uj}$ – parameters of the equation (3) of j -th cycle of the pulsation, t – time of jig operation.

The derivative of the media density as a function of time is as follows:

$$\frac{d\rho(t)}{dt} = A_j \cdot e^{-\alpha_j \cdot t} \left(\omega_j \cos(\omega_j t - \psi_j) + \alpha_j \sin(\omega_j t - \psi_j) \right) \quad (4)$$

Equation (4) can be used for determination of the relation between the time of measurement t_s and the derivative $d\rho/dt$:

$$t_p = f\left(\frac{d\rho}{dt}\right) \quad (5)$$

Let us normalize the parameters in equation (5) in the range (0,1):

$$t_N = \frac{t - t_0}{t_{\max} - t_0} \quad (6)$$

$$\left(\frac{d\rho}{dt}\right)_N = \left(\frac{d\rho(t)}{dt} - \left(\frac{d\rho}{dt}\right)_{\min}\right) \cdot \left(\left(\frac{d\rho}{dt}\right)_{\max} - \left(\frac{d\rho}{dt}\right)_{\min}\right)^{-1} \quad (7)$$

where:

t_N – normalized time [0,1],

t_0 – the beginning of the cycle pulsation,

t_{\max} – the end of the cycle pulsation,

$(d\rho/dt)_N$ – normalized derivative $d\rho/dt$,

$(d\rho/dt)_{\min(\max)}$ – expected (minimum/maximum) value of $d\rho/dt$ during the pulsation cycle.

The time of measurement t_s should depend on the value of the derivative $d\rho/dt$ and not on its sign. Hence the equation (4) should be rewritten as follows:

$$t_{sN} = f\left(\left|\left(\frac{d\rho}{dt}\right)_N\right|\right) \quad (8)$$

The time derivative $d\rho/dt$ expressed by equation (4) before and after the standardization is shown in figure 5.

Values of the time of measurement t_s can be calculated from normalized values (equation 8) as follows:

$$t_s = (t_{s(\max)} - t_{s(\min)}) \cdot t_{sN} + t_{s(\min)} \quad (9)$$

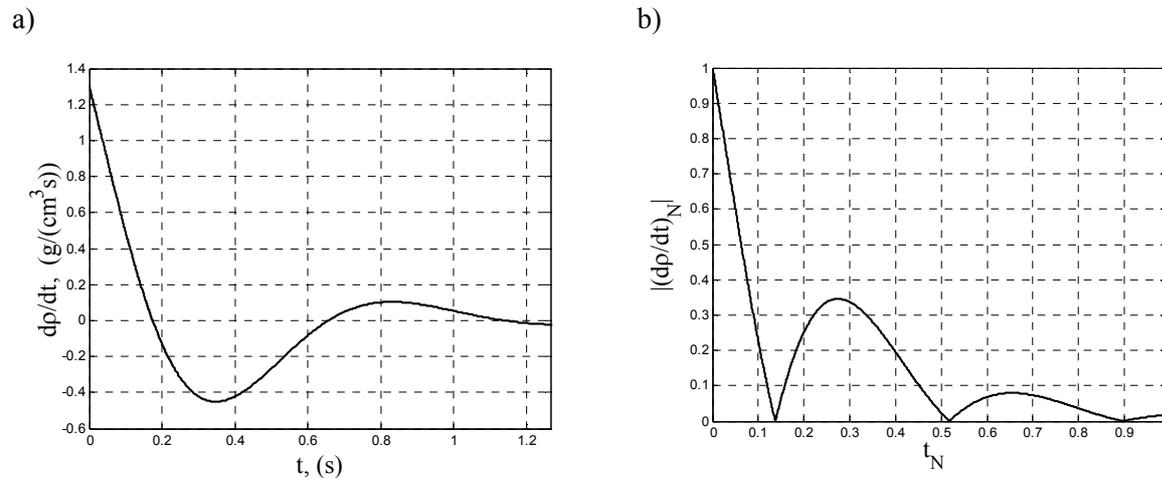


Figure 5. The derivative dp/dt as a function of time (a) before and (b) after standardization in the range $[0,1]$.

3. Simulation analysis

The simulation analysis was performed using the Matlab software package. The radiometric density meter was modeled by a generator of the discrete Poisson noise (GDPN) with the mean value of the intensity of pulses modulated by the measured density [9, 13]. The block scheme of the simulation model is shown in figure 6.

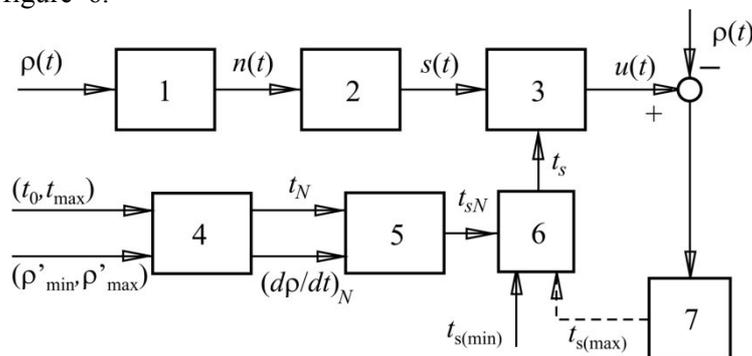


Figure 6. The block scheme of the simulation model
 1 – measuring head, 2 – generator of a discrete Poisson noise, 3 – counter of pulses, 4 – normalization, 5 – computing t_{sN} using one of the equations (10)-(13), 6 – denormalization, 7 – computing of the criterion value (eq. 2).

To establish a proper relation between the time of measurement and the time derivative of the density, the following relations were tested:

$$t_{sN} = \left(1 - \left|\left(\frac{d\rho}{dt}\right)_N\right|^2\right)^{0.5} \tag{10}$$

$$t_{sN} = -\left|\left(\frac{d\rho}{dt}\right)_N\right|^2 + 1 \tag{11}$$

$$t_{sN} = -\left|\left(\frac{d\rho}{dt}\right)_N\right| + 1 \tag{12}$$

$$t_{sN} = e^{-a \cdot \left| \left(\frac{d\rho}{dt} \right)_N \right|} \quad (13)$$

a – coefficient (range 2 - 5).

Relations (10) to (13) are presented in figure 7.

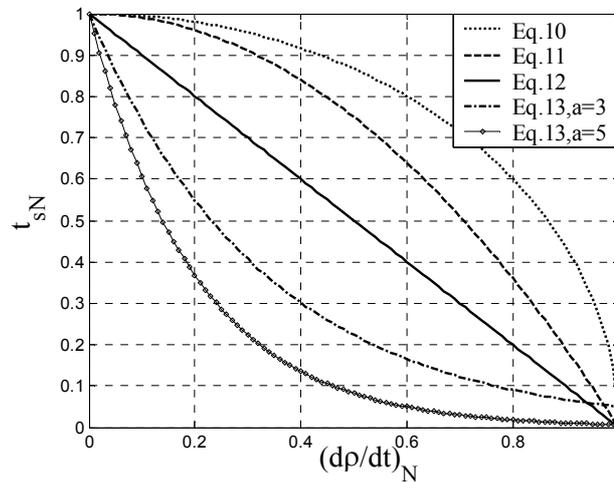


Figure 7. Functions used for calculation of the normalized time of measurement t_s .

The simulation analysis was performed for two cycles of pulsations in a jig. The generator of a non-stationary discrete noise of the Poisson distribution (GDNP) was used as a source of pulses at the output of the radiation detector. The detailed description of the simulation model was presented in [9, 13]. The series of pulses ($N_i = 2456$) modeled density changes during two cycles of pulsations of the coal/water bed. Changes in density during two cycles were described by equation (3) with the following parameters: $A_1 = 0.2$, $\alpha_1 = 3.04$, $\omega_1 = 6.50$, $\psi_1 = 0$, $\rho_{u1} = 1.39$ (for the first cycle in the time range 0 - 1.270 s) and $A_2 = 3.74$, $\alpha_2 = 2.60$, $\omega_2 = 6.77$, $\psi_2 = 2.32$, $\rho_{u2} = 1.40$ (for the second cycle in the time range 1.247 - 2.457 s). The minimum time of measurement was set to $t_s = 11$ ms and the maximum time was in the range 11 - 230 ms. The elementary time of simulation was $\Delta t = 1$ μ s, but the sample time necessary for calculation of MSE_c value was assumed as 1ms. The results of simulation are summarized in table 1 and figure 8. Figure 8a shows values of MSE_c (criterion 2) as a function of constant time of measurement t_s and figures 8b-f show values of MSE_c as functions of $t_{s(max)}$ for variable time of measurement t_s .

Table 1. Summary of simulation results

t_s (ms)	$t_{s(max)}$ (ms)	Equation	MSE_c , ($10^{-4} \cdot g^2/cm^9$)
37	-	-	2.770
-	80	(10)	1.191
-	73	(11)	1.158
-	108	(12)	1.104
-	78	(13), $a=2$	1.252
-	139	(13), $a=3$	0.999
-	189	(13), $a=4$	1.067
-	256	(13), $a=5$	1.048

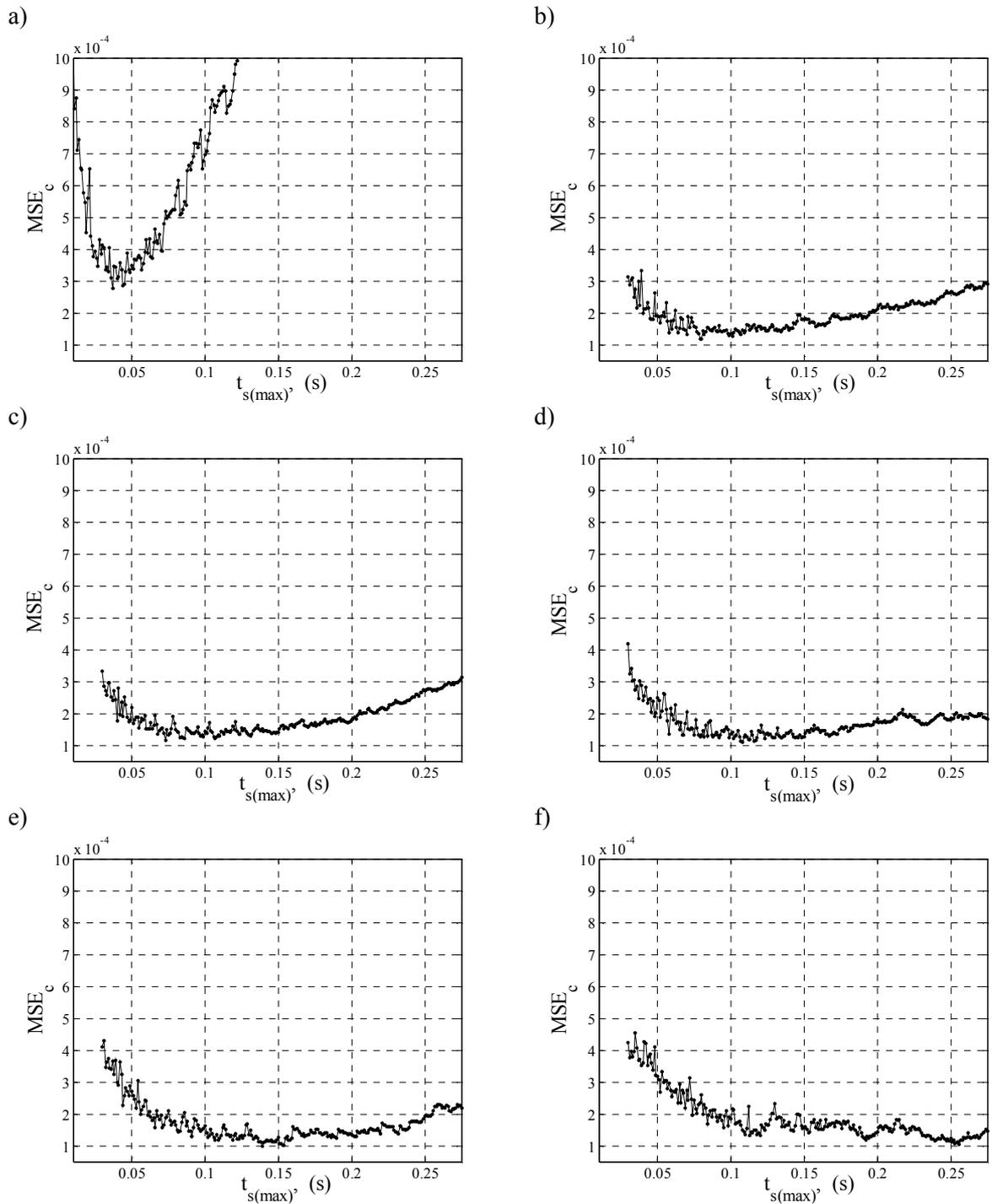


Figure 8. Values of MSE_c criterion (2) as a function of: a) constant time of measurement t_s and a function of variable time of measurement t_s determined by the maximum value $t_{s(max)}$ according to equation b) (10), c) (11), d) (12), e) (13), a = 3, f) (13), a = 5.

The results of simulation show better accuracy in the dynamic measurement of density changes for the variable time of measurement t_s than for the constant time t_s (for all tested functions $t_{s,N} = f(|(d\rho/dt)_N|)$). The best results have been obtained for exponential equations (13) and for the linear equation (12). Figure 9 shows the simulated signals $\rho(t)$ and $u(t)$ for the constant (figure 9a) and variable times of measurement t_s (figures 9b,c,d). Simulated functions $u(t)$ differ slightly in the analyzed cases. For the constant time of measurement (figure 9a) a higher shift of the phase between $u(t)$ and $\rho(t)$ can be observed compared to figure 9b and figures 9c,d. Fluctuations of $u(t)$ are lower for the variable time of measurement (figure 9b and figures 9c,d).

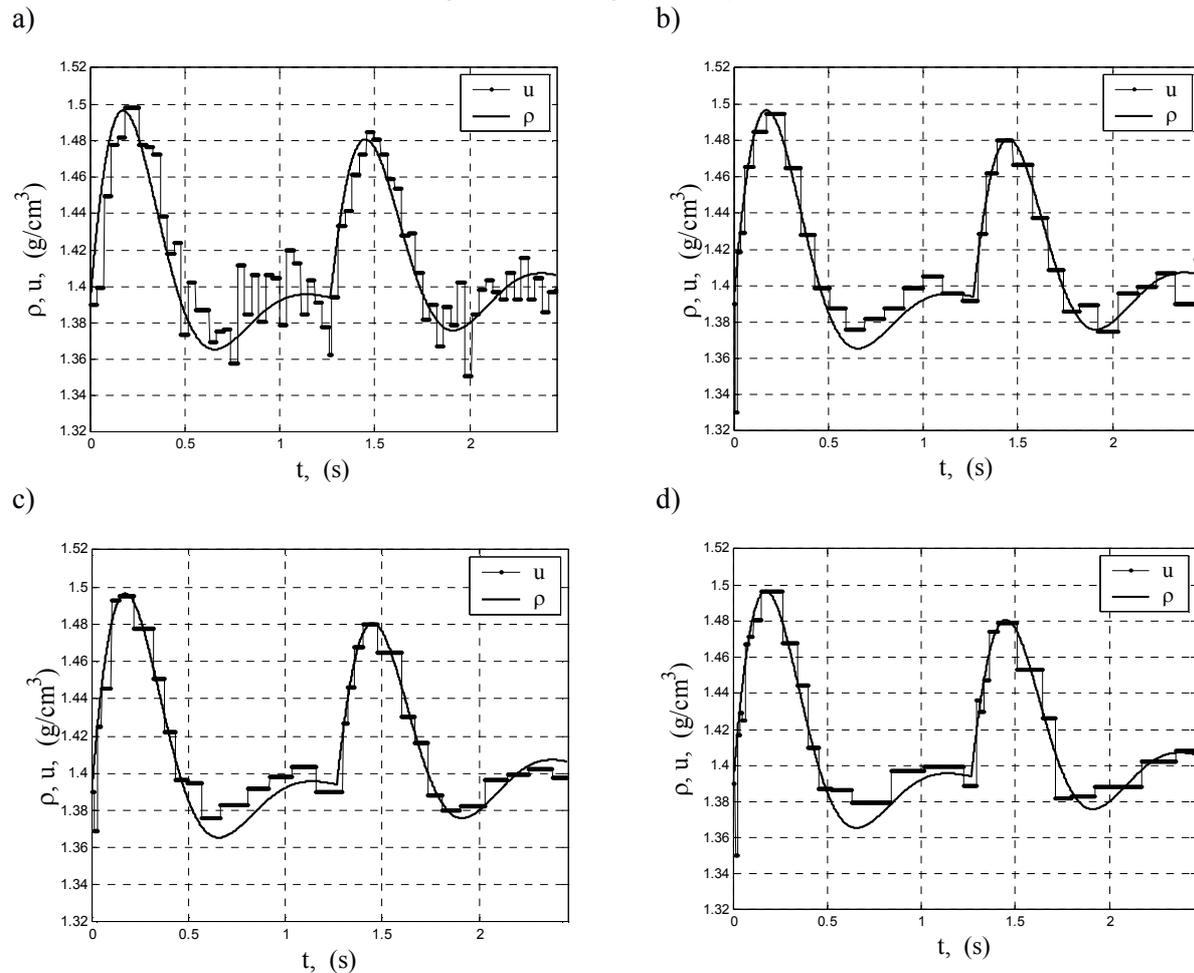


Figure 9. Output signals $u(t)$ for a) constant time of the measurement $t_s = 37\text{ms}$ and time of the measurement determined from b) eq. (12) at $t_{s(\text{max})} = 108\text{ ms}$ c) eq. (13) at $t_{s(\text{max})} = 139\text{ ms}$ and $a = 3$ and d) eq. (13) at $t_{s(\text{max})} = 256\text{ ms}$ and $a = 5$.

4. Conclusions

Coal separation process in a jig to a great extent depends on the dynamics of coal particles moving in the coal/water bed resulting in changes in the bed density. These changes can be monitored by a radiometric density meter placed at the edge of the upper gate discharging the coal concentrate. The shape of density changes in one cycle of pulsations (ca. 1.0 - 1.5 s) can be usually approximated by a sinusoid function with the exponentially decreasing amplitude and is repeated in the subsequent cycles of pulsations. The shape of changes in density differs from cycle to cycle, but this process is slow enough to use the information gained during a particular cycle to process data in several subsequent cycles.

The signal from the radiation detector is a non-stationary discrete process described by the Poisson distribution. The number of counted pulses during the time of measurement t_s is calibrated in density units. The time of measurement is usually constant in industrial radiometric monitors. The dynamic error of measurement in the case of changes in density (how accurately the changes are reproduced) depends on the time of measurement t_s and can be minimized for the optimal t_s . The optimal time of measurement depends on the shape of changes in density. Better results can be achieved for discrete filters with parameters adapting on-line to changes in density during a cycle. The basic problem of these methods is how to determine time derivative for a highly noisy non-stationary signal from the radiation detector.

An alternative method of signal filtration, discussed in this paper, is proposed for the variable time of measurement during a cycle of pulsations. Good results can be achieved for a linear relation between the time of measurement and time derivative of the density. The density time derivative can be determined for a long period of time on the basis of industrial tests of average changes in density in subsequent cycles of pulsations. In this case, the dynamic error of measurement MSE_c can be reduced by half compared to the optimal constant time of measurement.

The above results suggest that it is possible to further improve the presented method of density signal filtration by using the identified change in density in one cycle to adjust parameters of the algorithm generating the variable time of measurement in the next cycle or several cycles. This adaptive method will be the subject of future research.

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