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APPLYING OF DISCRETE KALMAN FILTER TO PROBLEM OF MEASURING OF LIQUID PROPELLANT LEVEL UNDER CONDITIONS OF SWING

The article is devoted to designing of a discrete Kalman filter for solving problem of measurement of propellant level in launch vehicle tanks during load operation under conditions of launch platform swing as well as to some results of study of effectiveness of designed filter.

Keywords: launch vehicle, level gauge, Kalman filter

Dosing operation for tanks of sea based launch vehicles (LV) such as LV of space launch systems “Sea Launch” goes on under conditions that are significantly different to conditions in which ground based rockets are loaded. A feature of sea based system is that a launch pad where rocket is installed is non static. Launch pad being part of launch platform (LP) moves together with LP swinging under influence of sea waves. Rocket makes oscillating motions deviating from vertical with angles about one degree. An error that could significantly decrease loading accuracy and respectively reduce launch vehicle performance [1] occurs during liquid propellant level measurement process provided by dosing system (Level Monitoring System – LMS) sensors that are usually located at some distance from a longitudinal tank axis. Using of hydraulic dampers to decrease influence of rocket swing (that from point of view of level measuring is seen as a respective periodic deviation of liquid surface from a nominal position that is a perpendicular to longitudinal tank axis plain) on dozing accuracy is ineffective because frequency of that oscillations is ten times lower than frequency of free liquid oscillations inside tank to suppress which hydraulic dampers are dedicated. There is another way to achieve appropriate measurement accuracy and this one is an applying of algorithmic methods for filtering sensor signal. One of the most effective methods of filtering is a discrete Kalman filter.

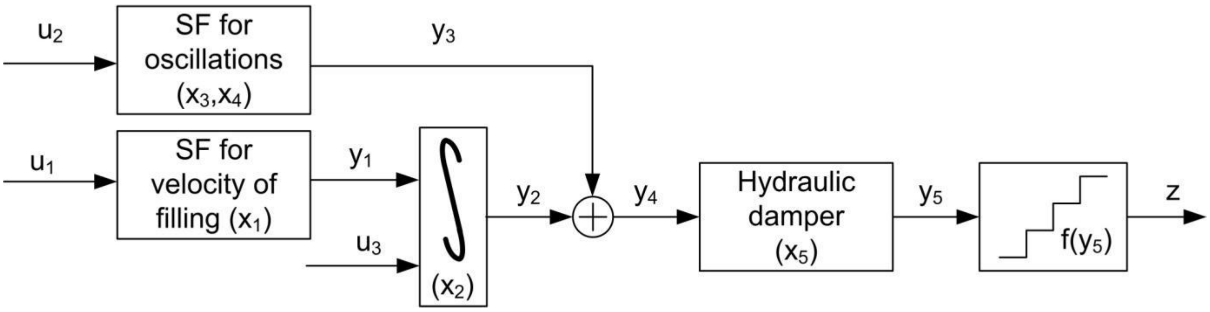
This article is devoted to designing of a discrete Kalman filter for solving the problem of measurement of propellant level in LV tanks during load operation under conditions of LP swing as well as to some results of study of effectiveness of designed filter.

A paper [2] presented a model for simulation of liquid propellant level measuring process going on under conditions of swing and this model could become a base of discrete Kalman filter for digital treatment of signal from continuous (along tank height) level sensor. In space state representation the model is described by two matrix equations. First one describes a system movement in space states, another one represents an output:

$$\mathbf{x}_k = \mathbf{A}\mathbf{x}_{k-1} + \mathbf{B}\mathbf{u}_{k-1} \quad (1)$$

$$\mathbf{z}_k = \mathbf{C}\mathbf{x}_k + \mathbf{D}\mathbf{u}_k \quad (2)$$

Space states vector is $\mathbf{x}_k = \begin{bmatrix} x_{1k} & x_{2k} & x_{3k} & x_{4k} & x_{5k} \end{bmatrix}^T$. Input vector is $\mathbf{u}_k = \begin{bmatrix} u_{1k} & u_{2k} & u_{3k} & u_{4k} & u_{5k} \end{bmatrix}^T$. Output variable that is result of measuring is a scalar z_k. A model structure that includes shaping filters (SF) for simulation of liquid level oscillations and velocity of tank filling with required statistic characteristics is presented in picture 1.



Picture 1 Model structure

Hereinafter: y_1 – linear velocity of tank filling, y_2 – level of propellant in the tank, y_3 – liquid surface oscillations, y_4 – propellant level at the LMS sensor location point, y_5 – propellant level inside hydraulic damper shell, z – value of propellant level measured by LMS sensor. All values y_i, z are measured along longitudinal tank axis from one common point of reference.

Matrix in equations (1) and (2) are like this:

$$\mathbf{A}=\begin{bmatrix} \dfrac{T_{à}-\dfrac{\Delta t}{2}}{T_{à}+\dfrac{\Delta t}{2}} & 0 & 0 & 0 & 0 \\ \dfrac{T_{à}\Delta t}{(T_{à}+\dfrac{\Delta t}{2})^2} & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & -a_2 & -a_1 & 0 \\ \dfrac{T_{à}\Delta t^2}{2(T_{à}+\dfrac{\Delta t}{2})^2} & \Delta t & b_2 & b_1 & \dfrac{T_{ó}-\dfrac{\Delta t}{2}}{T_{ó}+\dfrac{\Delta t}{2}} \end{bmatrix} \quad \mathbf{B}=\begin{bmatrix} 1 & 0 & 0 & 0 & 0 \\ \dfrac{\Delta t}{2(T_{à}+\dfrac{\Delta t}{2})} & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \\ \dfrac{\Delta t^2}{4(T_{à}+\dfrac{\Delta t}{2})} & 0 & \dfrac{\Delta t}{2} & 0 & 0 \end{bmatrix}$$

$$\mathbf{C}=\begin{bmatrix} \dfrac{T_{à}\Delta t^3}{4(T_{à}+\dfrac{\Delta t}{2})^2(T_{ó}+\dfrac{\Delta t}{2})} & \dfrac{\Delta t^2}{2(T_{ó}+\dfrac{\Delta t}{2})} & \dfrac{b_2\Delta t}{2(T_{ó}+\dfrac{\Delta t}{2})} & \dfrac{b_1\Delta t}{2(T_{ó}+\dfrac{\Delta t}{2})} & \dfrac{T_{ó}\Delta t}{(T_{ó}+\dfrac{\Delta t}{2})^2} \end{bmatrix}$$

$$\mathbf{D}=\begin{bmatrix} \dfrac{\Delta t^3}{8(T_{à}+\dfrac{\Delta t}{2})(T_{ó}+\dfrac{\Delta t}{2})} & 0 & \dfrac{\Delta t^2}{2(T_{ó}+\dfrac{\Delta t}{2})} & 0 & 0 \end{bmatrix} \qquad (3)$$

To explore system state via variables that reflect real physical values it is convenient to use the expression below:

$$\mathbf{y}_k=\mathbf{G}\mathbf{x}_k\text{, where} \qquad (4)$$

$$\mathbf{G}=\begin{bmatrix} \dfrac{T_{à}\Delta t}{(T_{à}+\dfrac{\Delta t}{2})^2} & 0 & 0 & 0 & 0 \\ \dfrac{T_{à}\Delta t^2}{2(T_{à}+\dfrac{\Delta t}{2})^2} & \Delta t & 0 & 0 & 0 \\ 0 & 0 & b_2 & b_1 & 0 \\ \dfrac{T_{à}\Delta t^2}{2(T_{à}+\dfrac{\Delta t}{2})^2} & \Delta t & b_2 & b_1 & 0 \\ \dfrac{T_{à}\Delta t^3}{4(T_{à}+\dfrac{\Delta t}{2})^2(T_{ó}+\dfrac{\Delta t}{2})} & \dfrac{\Delta t^2}{2(T_{ó}+\dfrac{\Delta t}{2})} & \dfrac{b_2\Delta t}{2(T_{ó}+\dfrac{\Delta t}{2})} & \dfrac{b_1\Delta t}{2(T_{ó}+\dfrac{\Delta t}{2})} & \dfrac{T_{ó}\Delta t}{(T_{ó}+\dfrac{\Delta t}{2})^2} \end{bmatrix} \qquad (5)$$

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There are following constant values: $T_{à}$ – time constant of attenuation in a correlation function of linear velocity of tank filling, $T_{б}$ –time constant in a first order system that represents a hydraulic damper model, Δt – sampling period. Some coefficients were introduced:

$$a_1 = \frac{2 - \frac{8b}{\Delta t^2}}{1 + \frac{2a}{\Delta t} + \frac{4b}{\Delta t^2}}, \quad a_2 = \frac{1 - \frac{2a}{\Delta t} + \frac{4b}{\Delta t^2}}{1 + \frac{2a}{\Delta t} + \frac{4b}{\Delta t^2}}, \quad b_1 = \frac{2}{1 + \frac{2a}{\Delta t} + \frac{4b}{\Delta t^2}}, \quad b_2 = \frac{2}{1 + \frac{2a}{\Delta t} + \frac{4b}{\Delta t^2}}, \tag{6}$$

where $a = \dfrac{2\mu}{\mu^2 + \beta^2}$ $\qquad b = \dfrac{1}{\mu^2 + \beta^2}$

Symbols applied: μ – coefficient of irregularity in description of signal model like “an irregular swing” type that generated by SP of oscillations, β – predominant frequency in “an irregular swing” type signal. Inputs u_1 and u_2 are white Gauss noise with variance:

$$D_1 = \frac{2T_{à}D_{ñ}}{\Delta t} \quad \text{and} \quad D_2 = \frac{2aD_{\alpha}}{\Delta t}R, \ \text{where} \tag{7}$$

$D_{ñ}$ –a variance of tank filling velocity, D_{α} – variance of LV inclination angle α in direction to sensor, R – distance between tank longitudinal axis and sensor.

Input u_3 is used to enter some determinate signal during simulation.

LMS level sensors could be continuous or discrete type [3]. Formula (2) covers only case of continuous measurement and then $z = y_5$. For simulation of discrete measurement a quantization with a permanent step should be applied to output:

$$z = \left[\frac{y_{5k} - h_0}{\delta} + \frac{1}{2}\right] + h_0, \ \text{where} \tag{8}$$

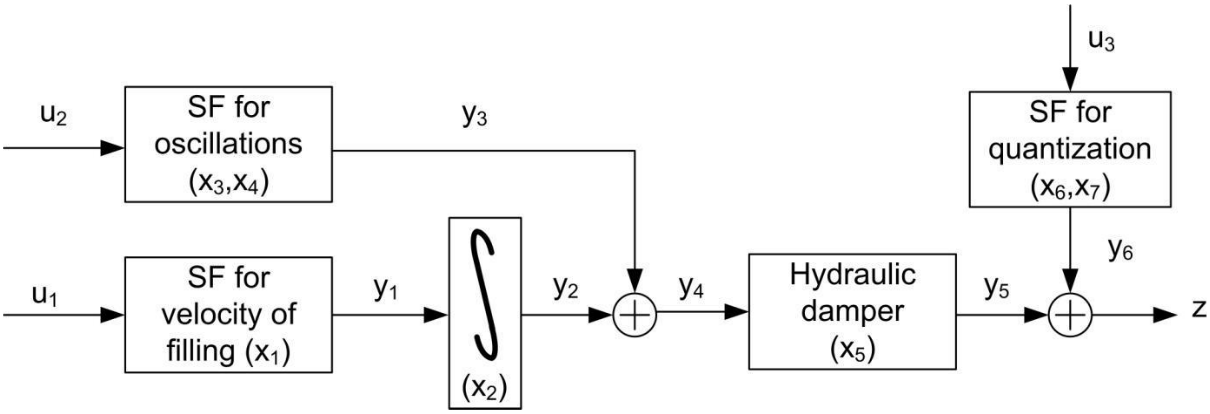
h_0 –height of zero level of a LMS sensor measured along longitudinal tank axis from a common point of reference, δ – quantization step (along tank height).

Expression (8) together with (1)÷ (5) is a simulation model capable of generating of signal sequence that adequately reflects a process of tank filling and measuring of liquid propellant level by discrete sensor under conditions of LP swing. But this model is not suitable for discrete Kalman filter due to significant nonlinearity of relation (8). Building of linear discrete Kalman filter for processing of signal from discrete level sensor could be made as a follow.

1. We will use the mathematical model (1) ÷ (3) to describe the observed process.

2. We will suppose the sensor static characteristic as a linear $z = y_5$.

3. We will consider the deviation of real static characteristic (8) from assumed linear characteristic as a random value or "a quantization noise". To simulate the quantization noise we will introduce one more SP to the model (pic. 2).



Picture 2 Model of process with SF for quantization

In this case the quantization noise is not white. This conclusion is a consequence of the fact that float discrete level sensors with inductive link between float and sensitive circuit are used in LMS as discrete level gauges. A quantization step of these sensors is 5-6% of measurement range [4] and no less than 10 mm. Level of liquid passes one discrete quantization level of sensor for 20−60 seconds but sampling period for such type of measurements is no more than one second. When quantization step is big and velocity of variation of input signal is low then rounding of sequence of impulses occurs to the same side, to the same value. Quantization error at certain point of time becomes to be depended on its previous value and therefore can't be considered as a white noise.

Guided by the approach described in [5] we assume correlation function of discrete random process that represents the quantization error of the described type in this form:

$$K(m) = \frac{\delta^2}{12}\frac{K_V(m)}{\sigma^2}\left[1 - 6\left|\frac{m\Delta t}{T_ñ} - l\right| + 6\left|\frac{m\Delta t}{T_ñ} - l\right|^2\right], \text{ where} \qquad (9)$$

m – number of sampling periods of time between two impulses, $K_V(m)$ –correlation function of linear velocity of tank filling, σ –standard deviation of linear velocity of tank filling, l –integer part of quotient $\frac{m\Delta t}{T_ñ}$, $T_ñ$–average time period of

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passing one discrete quantization level by liquid surface $T_ñ = \frac{\delta}{V_ñ}$, where $V_ñ$ – average linear velocity of tank filling during load operation.

We suppose that correlation function that describes signal of linear velocity of tank filling could be presented in the form:

$$K_V(m) = \sigma^2 e^{-\xi|m\Delta t|}$$, where (10)

$\xi = \frac{1}{T_a}$ –attenuation constant.

Discrete spectral density of signal described by correlation function (9) after consideration of (10) is presented in terms of pseudo frequency λ by the formula:

$$S(\lambda) = \frac{\delta^2}{2\pi^2 \Delta t} \sum_{i=1}^{\infty} \frac{1}{i^2} \frac{c_i \left(1 + b_i \lambda^2\right)(1 + \frac{\Delta t^2}{4} \lambda^2)}{\left|1 + c_i j\lambda + d_i (j\lambda)^2\right|^2}$$, where (11)

$$c_i = \frac{2\xi}{\xi^2 + (\frac{2\pi}{T_ñ} i)^2}, \qquad d_i = \frac{1}{\xi^2 + (\frac{2\pi}{T_ñ} i)^2}$$

If it is limited only by first harmonic then formula (11) describing the discrete spectral density will be represented in this form:

$$S(\lambda) = N \frac{(1 + b\lambda^2)(1 + \frac{\Delta t^2}{4} \lambda^2)}{\left|1 + aj\lambda + b(j\lambda)^2\right|^2}, \quad c = \frac{2\xi}{\xi^2 + \gamma^2}, \quad d = \frac{1}{\xi^2 + \gamma^2}$$, where (12)

$\gamma = \frac{2\pi}{T_ñ}$ –specific own frequency, i.e. average angular frequency of passing across quantization levels, N – level of spectral density that is defined by the way of integration (12) over the interval with infinity endpoints and then equating of obtained value to variance of quantization noise $D = \frac{\delta^2}{12}$. In accordance with [5]:

$$N = \frac{\delta^2}{12} \frac{c}{\Delta t}$$ (13)

On the base of formula (12) afrequency response of required shaping filter shall be:

$$H(j\lambda) = \frac{(1+\sqrt{d}j\lambda)(1+\frac{\Delta t}{2}j\lambda)}{1+cj\lambda+d(j\lambda)^2}\ , \tag{14}$$

and variance of white noise that should be entered via its input to provide required level of spectral density (13) of signal shaped on filter output shall be:

$$D_{áø} = \frac{\delta^2}{12}\frac{c}{\Delta t} \tag{15}$$

To pass from frequency response to discrete transfer function we performed substitution $\lambda j \to \frac{2}{\Delta t}\frac{1-z^{-1}}{1+z^{-1}}$ and have got:

$$H(z) = \frac{\dfrac{2+\dfrac{4\sqrt{d}}{\Delta t}}{1+\dfrac{2c}{\Delta t}+\dfrac{4d}{\Delta t^2}} + \dfrac{2-\dfrac{4\sqrt{d}}{\Delta t}}{1+\dfrac{2c}{\Delta t}+\dfrac{4d}{\Delta t^2}}z^{-1}}{1+\dfrac{2-\dfrac{8d}{\Delta t^2}}{1+\dfrac{2c}{\Delta t}+\dfrac{4d}{\Delta t^2}}z^{-1}+\dfrac{1-\dfrac{2c}{\Delta t}+\dfrac{4d}{\Delta t^2}}{1+\dfrac{2c}{\Delta t}+\dfrac{4d}{\Delta t^2}}z^{-2}} \tag{16}$$

After entering of obvious designations and reductions we have got discrete transfer function of SF for quantization noise:

$$H(z) = \frac{d_0+d_1z^{-1}}{1+c_1z^{-1}+c_2z^{-2}} \tag{17}$$

Considering definitions presented by pic. 2 it is in space state representation:

$$\begin{cases} x_{6k} = x_{7k-1} \\ x_{7k} = -c_2x_{6k-1} - c_1x_{7k-1} + u_{3k-1} \end{cases} \tag{18}$$

$$y_{6k} = -d_0c_2x_{6k} + (d_1 - d_0c_1)x_{7k} + d_0u_{3k} \tag{19}$$

We will modify the model of continuous measuring that was presented above (1) – (3) in such way that the model could be used at Kalman filter even in case of discrete measurements. After changes that are caused by appearance of additional equations (17) and (18) matrix **A**,**B**,**C** and **D** will take form presented bellow. Matrix equations (1) and (2) will remain in the same form.

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$$\mathbf{A} = \begin{bmatrix} \dfrac{T_{à} - \dfrac{\Delta t}{2}}{T_{à} + \dfrac{\Delta t}{2}} & 0 & 0 & 0 & 0 & 0 & 0 \\ \dfrac{T_{à}\Delta t}{(T_{à} + \dfrac{\Delta t}{2})^2} & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & -a_2 & -a_1 & 0 & 0 & 0 \\ \dfrac{T_{à}\Delta t^2}{2(T_{à} + \dfrac{\Delta t}{2})^2} & \Delta t & b_2 & b_1 & \dfrac{T_{ó} - \dfrac{\Delta t}{2}}{T_{ó} + \dfrac{\Delta t}{2}} & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 & -c_2 & -c_1 \end{bmatrix} \qquad (20)$$

$$\mathbf{B} = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ \dfrac{\Delta t}{2(T_{à} + \dfrac{\Delta t}{2})} & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ \dfrac{\Delta t^2}{4(T_{à} + \dfrac{\Delta t}{2})} & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 \end{bmatrix} \qquad (21)$$

$$\mathbf{C} = \begin{bmatrix} \dfrac{T_{à}\Delta t^3}{4(T_{à} + \dfrac{\Delta t}{2})^2(T_{ó} + \dfrac{\Delta t}{2})} & \dfrac{\Delta t^2}{2(T_{ó} + \dfrac{\Delta t}{2})} & \dfrac{b_2\Delta t}{2(T_{ó} + \dfrac{\Delta t}{2})} & \dfrac{b_1\Delta t}{2(T_{ó} + \dfrac{\Delta t}{2})} & \rightarrow \\ & \rightarrow & \dfrac{T_{ó}\Delta t}{(T_{ó} + \dfrac{\Delta t}{2})^2} & -d_0c_2 & d_1 - d_0c_1 \end{bmatrix}$$

$$\mathbf{D} = \begin{bmatrix} \dfrac{\Delta t^3}{8(T_{à} + \dfrac{\Delta t}{2})(T_{ó} + \dfrac{\Delta t}{2})} & 0 & d_0 & 0 & 0 & 0 & 0 \end{bmatrix} \qquad (22)$$

A recurrent algorithm of the discrete Kalman filter [6] consists of two phases: predict and update.

Predict

$$\hat{\mathbf{x}}_k^- = \mathbf{F}\hat{\mathbf{x}}_{k-1} \quad (23)$$

$$\mathbf{P}_k^- = \mathbf{F}\mathbf{P}_{k-1}\mathbf{F}^T + \mathbf{B}\mathbf{Q}\mathbf{B}^T \quad (24)$$

Update

$$\mathbf{K}_k = \mathbf{P}_k^-\mathbf{H}^T(\mathbf{H}\mathbf{P}_k^-\mathbf{H}^T + \mathbf{R})^{-1} \quad (25)$$

$$\hat{\mathbf{x}}_k = \hat{\mathbf{x}}_k^- + \mathbf{K}_k(\mathbf{z}_k - \mathbf{H}\hat{\mathbf{x}}_k^-) \quad (26)$$

$$\mathbf{P}_k = (\mathbf{I} - \mathbf{K}_k\mathbf{H})\ \mathbf{P}_k^-\text{, where} \quad (27)$$

It is applied following commonly used definitions that relate to current state of measuring and estimation process, i.e. to step k: $\hat{\mathbf{x}}_k$ –7x1 vector of state estimate, $\mathbf{P}_k$ – covariance 7x7 matrix of estimation errors, $\mathbf{Q}$ – covariance 7x7 matrix of input white noises, $\mathbf{K}_k$ –7x1 vector of Kalman gain, $\mathbf{R}$ – covariance matrix of observation noise (in this case – scalar R), $\mathbf{z}_k$ – observation vector (in this case – scalar z_k), $\mathbf{I}$ – identity 7×7 matrix. Matrix $\mathbf{F}$ and $\mathbf{H}$ are defined in this way: $\mathbf{F} = \mathbf{A}$, $\mathbf{H} = \mathbf{C}$.

To monitor system state via variables that reflect real physical values it is reasonable to use transformation $\hat{\mathbf{y}}_k = \mathbf{G}\hat{\mathbf{x}}_k$, where matrix $\mathbf{G}$ has the form (5).

Values z_k are indications received from output of discrete LMS level sensor at time k. During filter debugging and testing these values should be obtained from the output (8) of the model (1) – (3) (pic. 1).

Signals u_1, u_2 and u_3 are independent therefore in accordance with (7) and (15) matrix $\mathbf{Q}$ has the form:

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$$\mathbf{Q} = \begin{vmatrix} \frac{2T_{à}D_{ñ}}{\Delta t} & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & \frac{2aD_{\alpha}}{\Delta t}R & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & \frac{\delta^2}{12}\frac{c}{\Delta t} & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{vmatrix} \qquad (28)$$

R –is a scalar that, in substance, is a variance of the random variable $\mathbf{Du}_k$ and on the base of expressions (7), (15), (22) it is calculated like this:

$$R = \left(\frac{\Delta t^3}{8(T_{à} + \frac{\Delta t}{2})(T_{ó} + \frac{\Delta t}{2})}\right)^2 \frac{2T_{à}D_{ñ}}{\Delta t} + d_0^{\,2}\frac{\delta^2}{12}\frac{c}{\Delta t} \qquad (29)$$

To provide filtering of signal from continuous level sensor by the designed Kalman filter, matrix $\mathbf{A}$, $\mathbf{B}$, $\mathbf{C}$ and $\mathbf{D}$ shall be defined by expression (3), and elements of matrix $\mathbf{Q}$ as well as scalar R shall be defined by formulas (28) and (29) considering that variance of signal u_3 is zero.

Series of simulations using model (pic. 1) to imitate signal from discrete LMS level sensor have been performed with the aim to confirm a capability and efficiency of the designed discrete Kalman filter in its application to the task of measuring of propellant level in LV tanks during load operation going on under conditions of launch platform swing. A second stage fuel tank of LV “Zenith” of “Sea Launch” system was selected as an example for simulation. Input data for calculations are indicative and were formed by the analogy with known samples. Geometric characteristics of tank, quantity of fuel inside tank and LP inclination angles during load operation were defined using document [7]. Supposed quantization step is 12 mm and assumed sampling period is one second. Modeling was performed in MATLAB environment and for that a specific set of scripts and functions was designed and tested there. Designed software is a program implementation of methodology of simulation and filtering presented in this paper. It provides simulations for process of tank filling with liquid propellant in different modes and under different conditions as well as algorithmic treatment of simulated LMS input signal by the means of discrete Kalman filter with imitation of forming of signals for load operation control. The software set permits to perform variations of all mentioned above parameters of measuring process and filtering as well as of ambient parameters. Thus it is created a possibility to estimate influence of those or other factors including constructive ones on principal characteristics of dosing system.

The performed works have confirmed a full capability of designed filter and have demonstrated that applying of discrete Kalman filter for processing of level sensor signal redsuces a value of random component of loading error related to LP swing and discreteness of sensor from ± 130 liters to ± 50 liters.

Findings

As a result of performed theoretical studies, the key content of which is presented in this article:

1. A discrete Kalman filter for solving problem of measurement of a propellant level inside LV tanks during their loading under conditions of launch platform swing have been developed.

2. It is developed a software set that provides simulations of filling process inside LV tank in different modes and under different loading conditions as well as it provides processing of level sensor signal obtained during simulations, by the means of discrete Kalman filter.

3. Simulation and estimation of efficiency of the designed discrete Kalman filter in its application to measurements processing at Level Monitoring System have been performed. Calculations made for selected example demonstrate that applying of Kalman filter could reduce a value of a loading error component related to LP swing and discreteness of sensor two and a half times.

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