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SYNTHESIS OF A MATHEMATICAL STRUCTURAL-FUNCTIONAL MODEL OF A DIGITAL ALL-PASS FILTER

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The research is devoted to the synthesis of a mathematical structural and functional model of a digital all-pass filter. The synthesized model provides a formalized description of a all-pass filer structure and its operation, and forms the basis for further analysis and software implementation in embedded digital signal processing systems. The digital all-pass filter, implemented in software on a microcontroller, can be used as a separate element in the signal path for correcting phase distortion and group delay that occur during signal transmission.

Introduction. Digital signal processing is one of the most important parts of modern embedded systems, telecommunications devices, and radio communication systems. The use of microcontrollers with integrated analog-to-digital converters, particularly the STM32 family, enables the implementation of digital filtering algorithms directly on the system's hardware platform after signal conversion. Software implementation of digital signal processing (DSP) algorithms on computes is discussed in [1], while the structural and functional representation of digital systems, considered in [2, 5], creates the prerequisites for aligning their mathematical description with subsequent software implementation on microcontrollers.

All-pass filters are used for phase correction and compensation for frequency-dependent group delay without significantly altering the amplitude spectrum. This is important for digital signal processing paths in embedded systems, where, after the ADC, there may be a need for phase or time correction of the

signal without additional distortion of its amplitude components. Research of the structure and synthesis of digital all-pass filters is presented in [3], and methods for generating a given phase response for recursive all-pass filters using optimization procedures are discussed in [4]. All-pass filters are also of practical interest in digital radio receiver paths in remote control systems. When a radio signal passes through the communication channel and individual filter sections, frequency-dependent phase shifts and group delays can occur, affecting the structure of the information signal. Using all-pass filters allow for compensation of such phase-time distortions without altering the amplitude spectrum.

An analysis of publications [2-5] reveals that existing research is primarily focused on digital processing algorithms, the structural representation of DSP systems, and mathematical methods for synthesizing and optimizing all-pass filters. However, insufficient attention has been paid to the synthesis of a comprehensive mathematical structural and functional model of an all-pass filter that simultaneously reflects the mathematical dependencies and functional relationships of its elements and that can be directly used as a basis for further implementation on a microcontroller platform.

The **aim of the research** is the development of a mathematical structural and functional model of a digital all-pass filter that would combine a mathematical description of the algorithm, functional relationships between its elements, and the possibility of further implementation on a microcontroller platform.

To achieve the aim of the research, a method for the synthesis of graphical-analytical models of digital signal processing structures with presenting the elements of the system in the form of functional structures and the possibility of multilevel decomposition, which was described in [2], has been used. In Fig. 1 the structural and functional representation of a number of blocks of a first-order all-pass digital filter are shown. This representation is formed on the basis of the main interactions of the forward and backward flows from the corresponding elements of the delays Z^{-1}, adders and multipliers to coefficients C and $-C$. The input signal $x(n)$ and the delayed samples $x(n\text{-}1)$, $y(n\text{-}1)$ of this signal form a sequence of functional transformations, the result of which is an output $y(n)$.

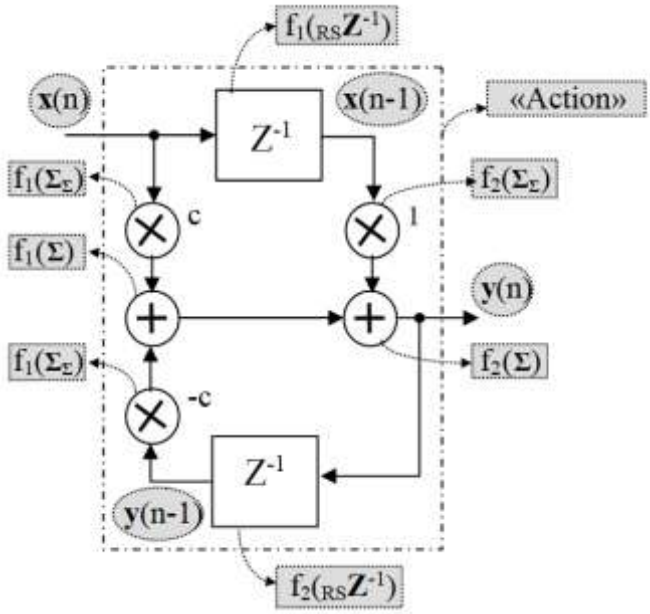


Figure 1 – Structural and functional representation of a first-order digital all-pass filter

The proposed in Fig. 1 representation shows the functional relationships between individual elements of the digital filter and the mathematical operations they perform on discrete signals, which corresponds to the structural-functional approach to modeling digital signal processing systems. The notations $f_1(\Sigma)$, $f_2(\Sigma)$ that denotes adders, $f_1({}_{RS}Z^{-1})$, $f_2({}_{RS}Z^{-1})$ that denotes delays, which in the DSP systems are usually memory registers, and $f_1(\Sigma_\Sigma)$, $f_2(\Sigma_\Sigma)$ that denotes multipliers, should be considered as functional operators of the corresponding structural elements of the model. This form of representation creates the basis for further synthesis of a mathematical structural-functional model of a digital all-pass filter with subsequent software implementation on a microcontroller as part of an embedded control, data acquisition and processing system. Fig. 2 presents a synthesized mathematical structural and functional model of a first-order all-pass digital filter.

The model implements recursive processing of the input signal $x(n)$ using delay elements, scaling (multiplication by coefficients), and algebraic summation operations. The input signal is simultaneously fed to the forward and scaled branches, and the output signal $y(n)$ through the delay element $f_2(_{RS}Z^{-1})$ forms the feedback signal $y(n\text{-}1)$, scaled (i.e. multiplied) by the coefficient $-c$ by means of the multiplier functional structure $f_1(\Sigma_\Sigma)$.

The functional transformations $f_1(\ldots)$ and $f_2(\ldots)$ respectively generate individual signal components and combine them into an output signal. When choosing the coefficient c, the structure provides a unity amplitude-frequency response, altering primarily the phase characteristics of the signal. The way in which the coefficient influences the frequency response of the filter is described in detail in [1]. Thus, the model can be used to mathematically describe and research phase transformations of digital signals without altering their amplitude spectrum.

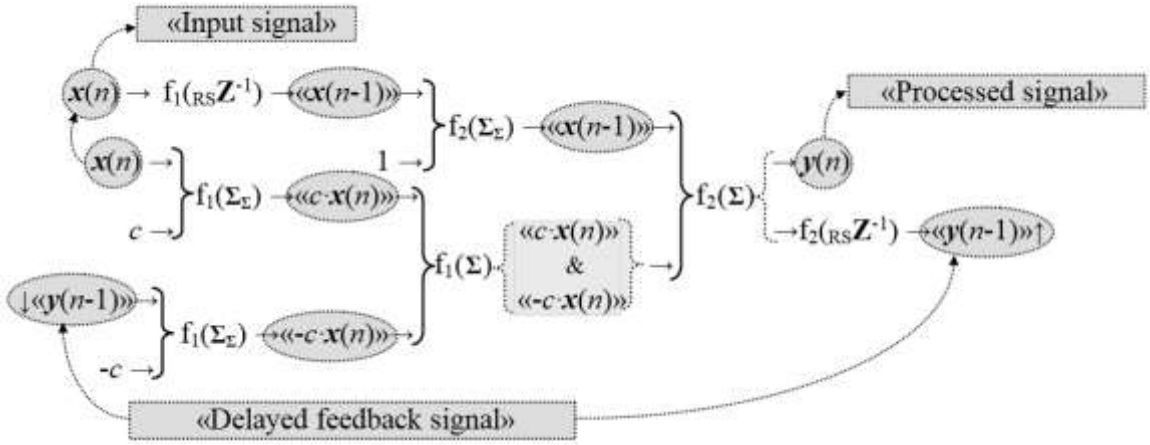


Figure 2 – Structural-functional model of a first-order all-pass digital filter

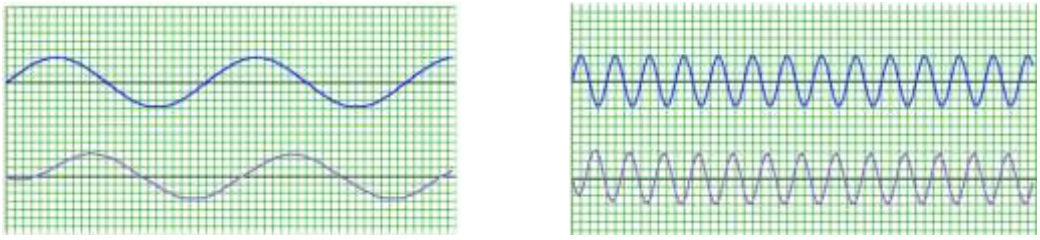
To test the functionality of the developed structural-functional model, its software implementation was carried out. The software implementation algorithm for an all-pass filter is as follows. The input signal is an array $X[0...N\text{-}1]$. The following steps are performed:

1. Initialize the output signal array Y with zero values.
2. Determine the filter parameters: f_s = 200 is the input signal frequency; $F_c = f_s/8000$ is the normalized sampling frequency (in this example the sampling frequency is 8 kHz).
3. Calculate the filter coefficient [1]:

$c = (\tan(\pi F_c)\text{-}1)/(\tan(\pi F_c)+1)$.

4. For each n from 1 to $N/4$, calculate: $Y[n] = cX[n] + X[n\text{-}1] - cY[n\text{-}1]$
5. Display the signal processing results.

Figures 3, a, b, show the results of processing input sinusoidal signals of varying frequencies with the implemented digital all-pass filter, and coincide with the results obtained in [1].



a b

Figure 3 – The result of digital processing of signals of different frequencies using all-pass filter

As can be seen from the figures, changing the signal frequency does not alter the amplitude, only the phase, indicating the correct software implementation of the filter.

Conclusion. A mathematical structural-functional model of an all-pass filter that shows the relationships between input and output discrete signals, delay elements, adders, and multipliers has been developed. The proposed approach allowed to formalize the filter description by combining its structure with a mathematical description of the operations performed on the signals. The practical significance of the obtained results is in the possibility of using this model as a basis for a software implementation of a

digital all-pass filter on microcontrollers. The model can be used in the development of embedded DSP systems, particularly for phase correction and compensation for frequency-dependent group delay in digital signal processing paths.

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FEATURES OF PUMPING CONCRETE MORTARS WITH A TWIN-PISTON PUMP AT LOW TEMPERATURES

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Abstract. The operating characteristics of a twin-piston pump during concrete mortar pumping at low temperatures are examined. The influence of changes in rheological properties on cylinder filling, pressure generation, and pump delivery rate is analyzed. Relationships between cylinder geometry, operating cycle frequency, and actual mortar delivery rate are established. A volumetric efficiency coefficient is used to account for cylinder filling conditions. Reduced mortar workability at low temperatures may decrease actual pump delivery and increase flow resistance. The main parameters affecting twin-piston pump operation under low-temperature conditions are identified.

Problem statement. Concrete mortar pumping at low temperatures involves changes in the interaction between the transported material and pump components. Temperature affects cement-based material rheology, particularly yield stress and viscosity, which may alter flow resistance within pump cylinders and delivery pipelines [1, 2]. Cylinder filling is particularly important for twin-piston pumps because this process occurs within a limited time and depends on mortar workability. Incomplete cylinder filling may reduce actual pump delivery even when the operating cycle frequency remains unchanged.

Research objectives. This study aims to analyze how concrete mortar temperature affects pumping conditions in a twin-piston pump. The research focuses on establishing relationships between cylinder geometry, operating cycle frequency, and pump delivery rate, as well as examining how changes in material rheology influence cylinder filling and the pressure required for mortar transport.

Main material. A twin-piston pump operates through alternating piston movements. While one piston forces concrete mortar into the delivery pipeline, the other performs a return stroke, allowing its cylinder to fill with material. At the end of each delivery stroke, the distribution valve switches position, reversing the cylinder functions. This arrangement provides alternating suction and discharge processes [3].

The theoretical mortar volume displaced during a single piston delivery stroke can be determined as

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