Acceleration Sensor Signal Based PWM Converter Control in Mold Oscillation Waveform Formation System

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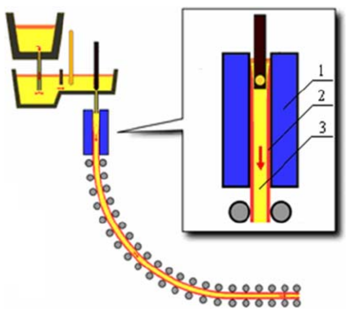
***Abstract* — The control system of PWM converter in hydraulic drive structure of the mold oscillation mechanism is used for preventing distortions of the mold movement. Its operation is based on collecting data from accelerometers. This system can be useful for many iron and steel works of Ukraine and overseas where continuous casting technology is used.**

Keywords — PWM converter; control; mold oscillation; IEEE standards, acceleration

I. Introduction

Today more than 60 % of slab steel billets are cast on slab continuous casting machines (CCM). These machines make it possible to produce billets of unlimited length with complete uniformity of structure throughout the length. The basis of CCM is the mold – the form, which is cooled by water. The liquid steel flows in the mold continuously. The surface layers of liquid steel are solidified in the mold. It creates the solid shell of billet, which has liquid phase inside. The continuous casting machine and the mold are shown in Fig. 1 [1].



1 – mold
2 – solidified metal
3 – liquid metal

Fig. 1. The continuous casting machine and the mold [1].

The oscillating movement of the mold (Fig. 2) [2] must be performed strictly along technological axis. It is especially important for slab mold. Its transverse displacements must be completely eliminated. Any distortions of movement increase friction forces and stress in shell of the billet. Kinematic and dynamic precision of movement of the mold oscillation table, where the mold is installed, must meet high requirements. When the mold oscillation waveform is distorted because of defects of the mold oscillation mechanism, the stability and safety of casting process decrease, the quality of slab billet surface deteriorates (Fig. 3) [3], and the probability of liquid steel breakthroughs increases. The control system of PWM converter in hydraulic drive structure of the mold oscillation mechanism is used for preventing distortions of the mold movement. Its operation is based on collecting data from accelerometers. This system can be useful for many iron and steel works of Ukraine and overseas where continuous casting technology is used.

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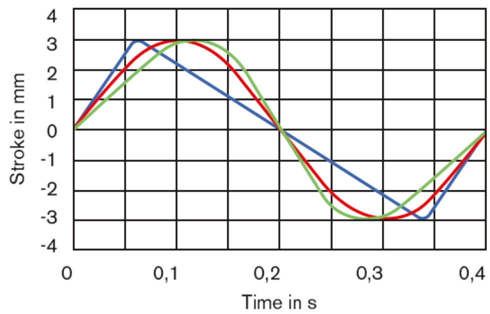

Fig. 2. The mold oscillation waveform [2].

The aim of the work is to develop the mold oscillation monitoring system for improving the control of the converter in the structure of mold oscillation mechanism.

The use of proposed system will increase productivity and lifetime of cast installation, will reduce the maintenance cost and the number of unplanned stops of the production process caused by failures of technological equipment.

Fig. 3. The defects of slab billet [3].

II. The Structure of Mold Oscillation Mechanism

Modern casting machines are equipped with mold oscillation mechanism based on hydraulic drive. Unlike mechanical drive, hydraulic drive makes it possible to implement both conventional sinusoidal oscillation modes as well as non-sinusoidal [4].

Fig. 4 shows the structure of casting machine mold oscillation system, where hydraulic drive is a control object. This is a closed loop system with displacement stabilization, which includes hydraulic cylinder, servovalve, linear motor, PWM converter, regulator, comparison element, acceleration sensor, reference signal generator. Servovalve regulates the flow rate of working fluid supplied to the hydraulic cylinder from the oil station (is not shown in the figure). The working fluid moves the hydraulic cylinder. The electric signal of negative feedback from the acceleration sensor on hydraulic cylinder is transmitted to the comparison element, which compares it with the reference signal. Their difference is transmitted to the regulator, which controls the PWM converter of linear motor with permanent magnets. The last one moves the throttle of servovalve and thus carries out the movement of the hydraulic cylinder.

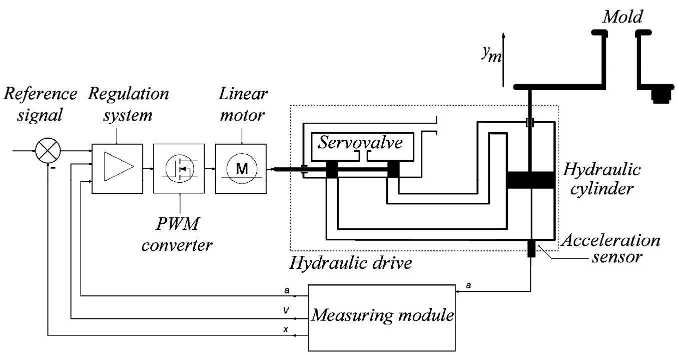

Fig. 4. The structure of mold oscillation system

The model of hydraulic drive as a load of PWM converter was considered in detail in [5]. The model of the unit of PWM converter + linear motor as inertial element was considered in [6]. The results of those works were used for synthesis of PWM converter control algorithms, which are formed by regulation system shown in Fig. 4.

Regulation system includes the proportional-integral regulator of servovalve displacement and combined regulator. The operation of the last one may be based on modal control principles and the conception of inverse problem of dynamics or on modal control and use of sliding modes. To implement this algorithm in practice, we should know additional coordinates of the control object – acceleration and velocity. This information is obtained by a measurement system based on measuring the accelerations with MEMS accelerometers.

III. The Structure of Measurement System

The system for measuring mold movement acceleration is shown in Fig. 5.

The measurement system makes it possible to keep track of the mold movement and to determine the trajectory deviation from reference signal. The system includes measuring modules (S1-S4) based on three-axis microelectromechanical accelerometers (MEMS), block of data collecting (BCD), personal computer (PC). The measuring modules contains the circuits of signal conversion. The communication between the measuring modules and the block of data collecting is carried out using CAN interface.

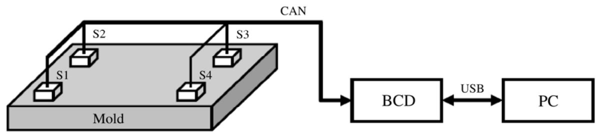

Fig. 5. The measurement system

The structure of the measuring module is shown in Fig. 6.

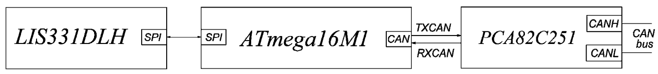

Fig. 6. The structure of the measuring module

The base of the measuring module is microelectromechanical accelerometer LIS331DLH, which interacts with microcontroller ATmega16M1 by SPI-interface. The microcontroller initializes the accelerometer, collects the acceleration data measured along the three axes, transmits the measured results into personal computer by the CAN interface. The chip PCA82C251 is CAN-transceiver, which provides the matching between the microcontroller signals and CAN-bus according to the standard ISO 11898.

The algorithm of the measurement system operation is shown in Fig. 7. Before beginning the measurements, the measuring modules are placed in control points on the mold surface. After starting the system, the initialization of measuring modules and their time synchronization with personal computer are accomplished. Next, the initial static accelerations along the three axes X, Y, Z (the projections of gravitational acceleration) are detected to take into account the installation inclination of the measuring modules (block 1 of the algorithm). After that, the measuring modules S1-S4 are automatically calibrated (the blocks 2-3 of the algorithm). As a result, the zero level for each module axis is adjusted, and the signal gains are found in order to optimal use of the measurement scale.

In the next step, the accelerations are measured by S1-S4 with given discretization frequency. The obtained data are transmitted into PC (the blocks 4-7 of the algorithm). The measuring process terminates when the quantity of the measurements reaches predetermined number. Then, the obtained measurement results are processed to calculate the trajectory of the mold movement (the blocks 8-10 of the algorithm).

The data obtained from BCD after normalizing procedure are processed in PC according to equations (1) and (2). As a result, we obtain the movement parameters of the installation points of measurement modules – velocity and displacement:

$$V(t) = V_0 + \int_{t_0}^{t} a(t)dt \,, \quad (1)$$

$$S(t) = S_0 + \int_{t_0}^{t} V(t)dt\,, \qquad (2)$$

where $V(t)$ – movement velocity; V_0 – initial velocity; $S(t)$ – displacement; S_0 – initial displacement of the mold surface.

Discrete integration is carried out according to the following equations:

$$v_c\left[(n+1)T_2\right] = v_c\left[nT_2\right] + \frac{u_q\left[(n+1)T_2\right]\cdot T_2}{k_{pr}}\,, \qquad (3)$$

$$x_c\left[(n+1)T_2\right] = x_c\left[nT_2\right] + v_c\left[(n+1)T_2\right]\cdot T_2\,, \qquad (4)$$

where $u_q[(n+1)T_2]$ – discrete function of the voltage, which is proportional to acceleration on discretization interval $(n+1)$; k_{pr} – proportionality factor; T_2 – discretization interval, which is determined by sensor characteristics and tract data transmission; $v_c[nT_2]$ and $v_c[(n+1)T_2]$ – calculated velocity on discretization interval n and $(n+1)$ respectively; $x_c[nT_2]$ and $x_c[(n+1)T_2]$ – calculated displacement on discretization interval n and $(n+1)$ respectively.

To avoid the accumulation of integration error the tracking of specific time moments on the curves of acceleration, velocity and displacement is accomplished. It is convenient to use matching to period or half-period of oscillations because the mold oscillations are periodic. In the time moments, which are multiples of oscillation period, the initial conditions of integration may be considered as zero.

The oscillation period is calculated using mean-value function of difference (MVFD) [7]. The quantity of samples are chosen in the way that two or more periods of oscillations are placed into them:

$$d(mT_2) = \sum_{m=0}^{j} \frac{u_q\left[nT_2\right]}{k_{pr}} - \frac{u_q\left[(n+m)T_2\right]}{k_{pr}}\,, \qquad (5)$$

where j – quantity of values in sample divided by 2.

Further, the minimums of MVFD are determined and the period of oscillations is calculated as a distance between two nearby minimums of the MVFD. The verification of the error absence and the correction of the integration initial conditions in calculating the movement velocity, if required, are carried out by comparison of velocity values in the time moments, which are multiples of oscillation period. After calculating the oscillation period, the integration is accomplished.

The deformations of the mold may be neglected because it is a tough plate. To find out the mold position in space, the data of three points on its surface, measured by S1-S3, are enough. The data from S4 is excessive and is used for verification of correctness of the mold movement trajectory calculation (the block 11 of the algorithm). The verification is performed by theoretical calculation of the fourth point movement trajectory using the information about the three points. The result of calculation is compared with the trajectory measured by the module S4.

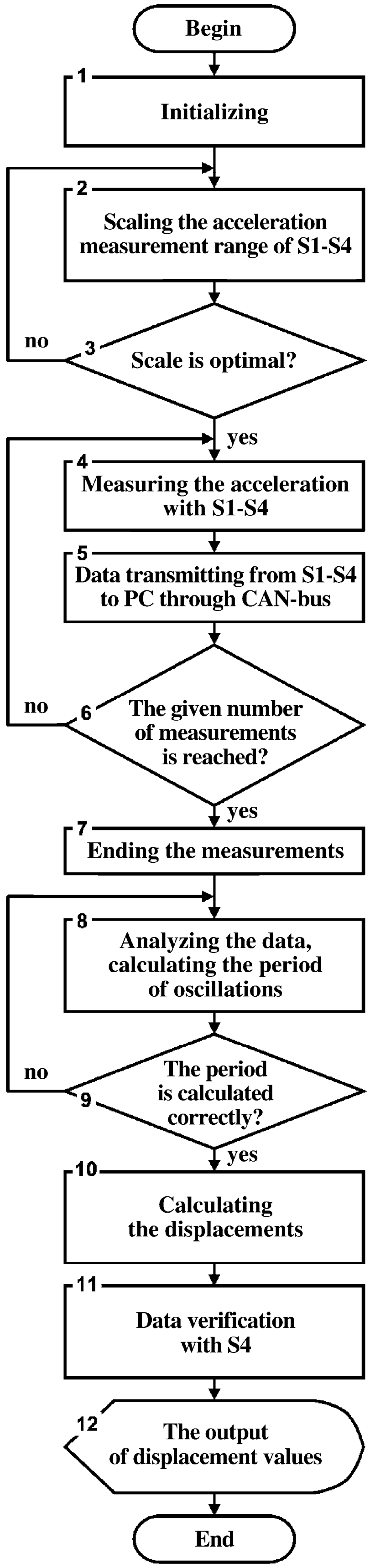

Fig. 7. The algorithm of the measurement system operation

The measured and calculated data are displayed (the block 12 of the algorithm) as two-dimensional time diagrams and as a dynamic three-dimensional model of the mold with movement trajectories of the four control points.

IV. USING THE STANDARDS

For communication between the measuring modules and the block of data collecting, the CAN Network ISO standard (ISO 11898) [8] is used. According to the ISO 11898 standard architecture, the OSI model is represented by two layers – the data-link layer and the physical layer. The data-link layer is the CAN-module of the microcontroller ATmega16M1 (Fig. 8). It receives and forms data sets according to the ISO 11898. The fragment of data transmitting is shown in Fig. 9 [9].

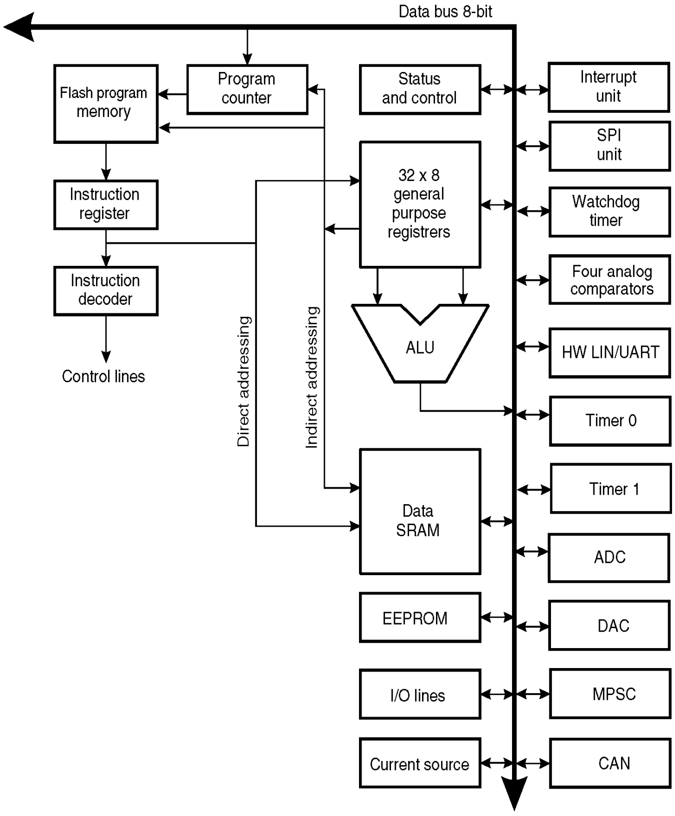

Fig. 8. The structure of the microcontroller ATmega16M1 [9]

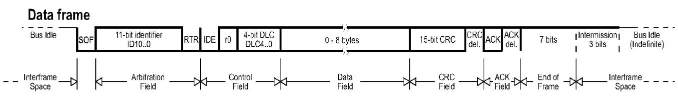

Fig. 9. Data frame CAN [9]

A message in the CAN standard frame format begins with the "Start Of Frame (SOF)", this is followed by the "Arbitration field" which consists of the identifier and the "Remote Transmission Request (RTR)" bit used to distinguish between the data frame and the data request frame called remote frame. The following "Control field" contains the "IDentifier Extension (IDE)" bit and the "Data Length Code (DLC)" used to indicate the number of following data bytes in the "Data field". In a remote frame, the DLC contains the number of requested data bytes. The "Data field" that follows can hold up to 8 data bytes. The frame integrity is guaranteed by the following "Cyclic Redundant Check (CRC)" sum. The "ACKnowledge (ACK) field" compromises the ACK slot and the ACK delimiter. The bit in the ACK slot is sent as a recessive bit and is overwritten as a dominant bit by the receivers which have at this time received the data correctly. Correct messages are acknowledged by the receivers regardless of the result of the acceptance test. The end of the message is indicated by "End Of Frame (EOF)". The "Intermission Frame Space (IFS)" is the minimum number of bits separating consecutive messages. If there is no following bus access by any node, the bus remains idle [9].

The physical layer is the chip of CAN-transmitter PCA82C251. It provides conforming the microcontroller signals to the CAN-bus standard according to ISO 11898. The internal structure of the transmitter is shown in Fig. 10 [10]. The device provides differential data transmitting through the bus and differential data receiving by the CAN controller. It is completely compatible with the ISO 11898-24 V standard [10].

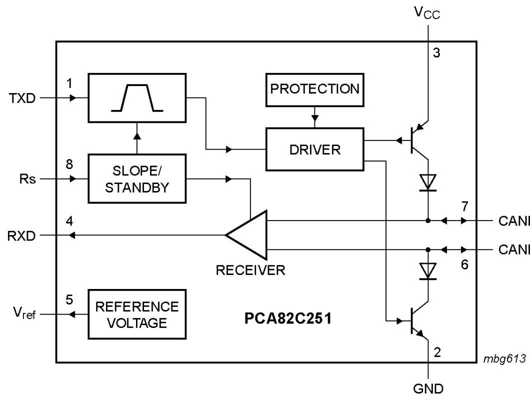

Fig. 10. The structure of the chip PCA82C251 [10]

The standard IEEE 1588-2008 [11] is used for coordinating the time of the measuring modules with system time of the personal computer. The time coordination is carried out right after starting the algorithm of the measurement system operation. Let’s consider this procedure in detail. At the beginning of the initializing, the personal computer (master) transmits the data of system time t1 through the CAN-interface. Measuring module (slave) records the time t2 of the data arrival. The time t2 is the sum of system time t1, the time offset and the time of data transmitting. Then, the slave transmits its current time t3 to the master. The master traces the moment t4 of receiving the data and transmits it to the slave. Based on this information, the two linear equations are solved to calculate the time of data transmitting and the time offset on the slave side. It is required for the time correction of the measuring modules. This procedure is performed for each of four modules.

The standard IEEE 802.3i [12] is used for communication between the measuring personal computer and the process control server of the factory (Fig. 11). This communication is performed through Ethernet 10BASE-T interface. The process control server stores the measurement results of the mold displacements. Any client of the network can process these data using special software [13] to find out the malfunctions of the mold oscillation mechanism. The window of the evaluation of mold oscillation mechanism state using data visualization of the displacement measurements is shown in Fig. 12 [13]. It is used for teaching the system faulty states. The results of evaluation are written into database. It makes it possible to automate the diagnostic process of the oscillation mechanism state in future.

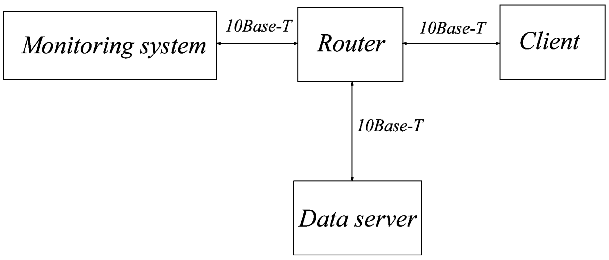

Fig. 11. The structure of the control network of the factory

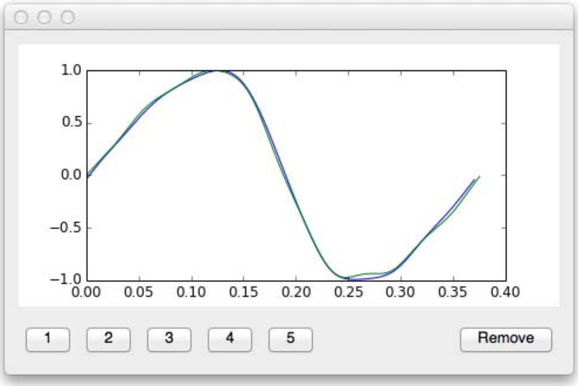

Fig. 12. The window of the system teaching [13]

V. Practical Implementation of the System

The algorithm is implemented in measuring-information system. The system successfully passed the tests at the Alchevsk Iron & Steel Works, PJSC. It was used for monitoring mold oscillation parameters. The basic technical parameters of the system: quantity of measurements per second (1600), resolution (0.5 mg), measurement time (3 s). The output data of the system are accelerations, velocities and displacements from three axes of four measuring modules. As a result of the test, it was found out that the designed algorithm is capable to provide the required accuracy of measurements of oscillation parameters. Thus, if the amplitude of the mold movement is 3mm, the accuracy of displacement measurement for one period of oscillations is 0.025 mm.

The hardware/software module is shown in Fig. 13. The software interface, designed using Python, is shown in Fig. 14.

VI. Conclusion

The tests of designed system in factory conditions confirmed its operability and effectiveness. It may be recommended for measuring acceleration in a control system of a converter in hydraulic drive of mold oscillation mechanism. The designed system can help to improve the control of the converter, to increase the extent of control automation, and therefore to increase the quality of the product.

Using the standards ISO 11898, IEEE 1588-2008, IEEE 802.3i made it possible to increase the flexibility of the system and to improve it with minimal expenses. Also, it provides conforming the technical characteristics to the level of full compatibility with structures of control systems of all iron and steel works.

In the future, the tests of the developed system in the structure of the mold oscillation mechanism is planned.

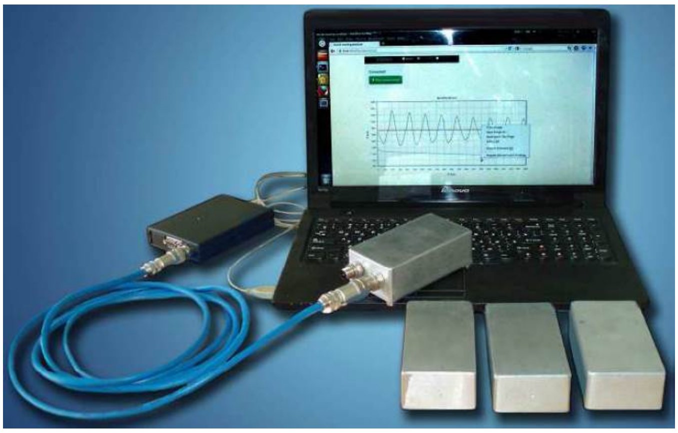

Fig. 13. The designed measuring-information system

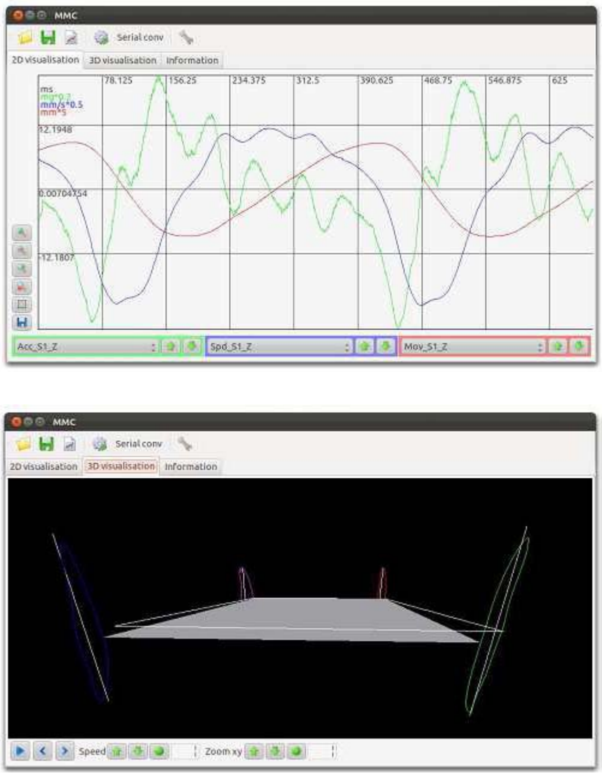

Fig. 14. The software interface

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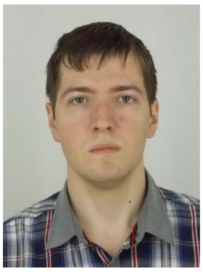

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