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MATHEMATICAL IDENTIFICATION OF THE MECHATRONIC COMPLEX FOR THE CONSTRUCTION OF MINI TUNNELS IN URBAN CONDITIONS

Alexey Grigoryevich Bulgakov*[1] Alexander Vakolyuk[2] Nikolay Glebov[2] Jens Otto[3]
[1]Southwest State University, Kursk, Russia
[2] South-Russian State Polytechnic University, Novocherkassk, Russia
[3]Technical University Dresden, Germany

This article is devoted to the development and investigation of the mathematical model of the mechatronic tunnel complex. The method for remote determination of the spatial position of the mini shield in the basic coordinate system is developed. The principle of constructing a laser system for determining the spatial coordinates of the tunnelling shield is offered. The exchange of information between the operator's console and the control equipment of the shield is shown.

Key words: Robotics and mechatronics, Mathematical identification, Control, Mini tunneling complex, Laser system

INTRODUCTION

To receiving the optimal control system for the tunneling shield, used in the laying of mini tunnels, it is necessary to develop its mathematical identification as a control object. It should be borne in mind that during the operation of the tunnel complex, various external and internal factors affect it, leading to a change in the spatial position of the shield and the direction of its motion. These factors should be taken into account in the compilation of the mathematical model of the complex [01].

MATHEMATICAL IDENTIFICATION OF THE TUNNELLING SHIELD

To ensure that the tunnel will be built according to the project, it is necessary that the longitudinal axis of the shield coincides with the axis of the tunnel on rectilinear sections or be tangent to it on curvilinear sections of the tunnel. Consequently, the task of controlling the directional movement of the shield (Figure 1) is reduced to controlling the position of the longitudinal axis of the shield relative to the tunnel axis by means of deviation hydraulic jacks.

The position of the longitudinal axis of the shield in the coordinate system $O_ПX_ПY_ПZ_П$, connected with the projected axis of the mini tunnel, is completely determined by the coordinates of its two points lying in the front and rear end planes. The point lying on the axis of the shield in the front end plane will be called the knife point, and its coordinates are $X_1Y_1Z_1$. The point lying on the axis of the mini shield in the rear end plane is called the tail point, and its coordinates are $X_2Y_2Z_2$.

The speed of the deviation of the knife (tail) point of the longitudinal axis of the minischit consists of the speed (V_y, V_z) of the turning point (TP) and the rotation speed of the mini shield around the turning point:

$$\frac{dZ_1}{dt} = V_z + a_1\frac{d\alpha}{dt};\ \frac{dZ_2}{dt} = V_z - a_2\frac{d\alpha}{dt};$$
$$\frac{dY_1}{dt} = V_y + a_1\frac{d\beta}{dt};\ \frac{dY_2}{dt} = V_y - a_2\frac{d\beta}{dt}, \quad 1)$$

where a_1, a_2 – the distance between the TP and the knife (tail) points, respectively; *α* и *β* are the angles between the projections of the shield axis in the XOZ, XOY plane and the positive direction of the OX axis.

The law for the formation of small angles *α* and *β* is obtained from the equations of moment equilibrium with respect to the axes $0_щY_щ$ and $0_щZ_щ$:

$$I_y\frac{d\omega_y}{dt} = r_zP - B_1\omega_y - B_2\alpha - f_mG\frac{D}{2} - Ga$$
$$I_z\frac{d\omega_z}{dt} = r_yP - B_1\omega_z - B_2\beta.$$

where I_y, I_z are the moments of inertia of the shield with respect to $O_щY_щ$ and $O_щZ_щ$; ω_y, ω_z are the angular speeds of rotation of the shield around the axes $O_щY_щ$ and $O_щZ_щ$; P is the resultant force of the P_1 ... P_i pushing hydraulic jacks and the elastic force arising in the pipe; r_y, r_z are the projections of the rad B_1 us of the vector r of the point of application of the resultant P on the axis $O_щY_щ$ and $O_щZ_щ$; B_1 is a coefficient that takes into account the viscous friction, determined by the properties of the rocks in which the construction of the mini tunnel and the parameters of the shield are made; B_2 is a coefficient that takes into account the geometry of the shield, the amount of clearance between the enclosure of the shield and the walls of the mine and the depth of pressing the shield into the ground; f_m is the coefficient of friction of the cabinet of the shield by breed; *G*, *D* - weight and outside diameter of the shield.

* *Southwest State University, Street 50 years of October, 94 Kursk, Russia, a.bulgakow@gmx.de*

The dynamics of the translational motion of the complex can be considered as the dynamics of a loaded piston of an equivalent hydraulic cylinder whose mass is equal to the total mass of the pistons of the hydraulic jacks of displacement. The equation of motion of the hydraulic jack is represented as:

$$m_{п}\ddot{X} = P_{н}A_{п}n_{г} - F_{сг} - C_{тр}\left(X - X_{щ}\right) - F_{тр} - \sigma V$$

where $m_{п}$ is the mass of the piston of the equivalent hydraulic jack; $P_{н}$ is the pressure drop in the cavities of the hydraulic cylinder; $A_{п}$ is the area of the piston of the hydraulic jack; $n_{г}$ – the the number of simultaneously connected hydraulic jacks; $F_{сг}$ is the frictional force of the piston against the wall of the hydraulic cylinder; $C_{тр}$ is the rigidity of a laid pipe at its deformation; X - displacement of the piston of an equivalent hydraulic jack; $X_{щ}$ - moving tunnel tunnel; $F_{тр}$ - frictional force on the rock of the shell embedded in the ground pipe; σ - coefficient of proportionality, taking into account the viscous friction of the complex over the rock; V - speed of movement of the pipe (mini shield).

The equation of the translational movement of the mini shield has the form:

$$m_{щ}\ddot{X}_{щ} = C_{тр}\left(X - X_{щ}\right) - F_{с}$$

where $m_{щ}$ - total weight of the mini-cabinet with the equipment; F_{c} - force of resistance of introduction of a mini shield in a ground in view of force of a friction of a cover of a mini shield on a breed.

Neglecting the frictional force of the piston against the wall of the hydraulic cylinder, as well as the mass of the piston, since it is small in comparison with the mass of the tunneling complex, the equation of the translational movement of the mini shield can be represented in the form:

$$m_{щ}\frac{d^2X}{dt^2} = P - F_{тр} - F_{с} - \sigma V$$

The speed of translational movement of the mini-panel V is determined from the equation of flow $Q_{н}$ of its hydraulic system in the following form:

$$Q_{н} = n_{г}A_{п}V + k_{ут}P_{н} + \frac{\upsilon n_{г}}{2E_0}\cdot\frac{dP_{н}}{dt}$$

where $k_{ут}$ is the leakage coefficient; υ is the equivalent volume of the working chamber of the hydraulic cylinder; E_0 is the effective value of the generalized elastic modulus.

Measurement of the deviation of the mini shield from the projected direction of motion is made using the system of determining the spatial coordinates described by expressions:

$$U_{н.пл.} = k_{д}Y_1;\; U_{х.пл.} = k_{д}Y_2$$

$$U_{н.пр.} = k_{д}Z_1;\; U_{х.пр.} = k_{д}Z_2$$

where $k_{д}$ is the transmission coefficient of the system for determining the spatial coordinates of the mini shield.

Thus, combining the presented equations, making assumptions about the absence of mutual influence of movements in the plan and profile, we obtain a system of equations describing the spatial motion of the mechatronic tunnel mini shield:

$$\frac{dY_1}{dt} = V\beta + a_1\frac{d\beta}{dt};\; \frac{dY_2}{dt} = V\beta - a_2\frac{d\beta}{dt};$$

$$\frac{dZ_1}{dt} = V\alpha + a_1\frac{d\alpha}{dt};\; \frac{dZ_2}{dt} = V\alpha - a_2\frac{d\alpha}{dt};$$

$$I_y\frac{d^2\alpha}{dt^2} + B_1\frac{d\alpha}{dt} + B_2\alpha = r_zP - f_mG\frac{D}{2} - aG;$$

$$I_z\frac{d^2\beta}{dt^2} + B_1\frac{d\beta}{dt} + B_2\beta = r_yP;$$

$$m_{щ}\frac{dV}{dt} = P - F_{тр} - F_{с} - \sigma V;$$

$$Q_{н} = n_{г}A_{п}V + k_{ут}P_{н} + \frac{\upsilon n_{г}}{2E_0}\cdot\frac{dP_{н}}{dt};$$

$$U_{н.пл.} = k_{д}Y_1;\; U_{х.пл.} = k_{д}Y_2;$$

$$U_{н.пр.} = k_{д}Z_1;\; U_{х.пр.} = k_{д}Z_2$$

Linearizing the equations of motion of the mini shield with respect to small deviations of the parameters, we obtain the differential equation of motion of the tunnel mini shield:

$$I_y\frac{d^3Z_1}{dt^3} + B_1\frac{d^2Z_1}{dt^2} + B_2\frac{dZ_1}{dt} =$$

$$= a_1(F_c + F_{тр})\frac{dr_z}{dt} + (F_c + F_{тр})Vr_z$$

Having studied the model of the mini-panel in the Simulink MATLAB package, graphs of the angular velocity ω_y, rotation angle α and the Z_1 coordinate of the knife point of the shield are obtained (Figures 2 and 3) with the following initial data: the mass of the mini shield is 13,500 kg; speed of movement mini shield - 12 m / shift; the resultant force of pushing hydraulic jacks is 4000 kN; the diameter of the mini shield is 1.22 m; length mini shield - 3 m; moment of inertia of the mini shield with respect to the axis $O_{щ}Y_{щ}$ I_Y≈11381 кг·м^2.

Analyzing the resulting graphs, we can say that the mini shield is an unstable object, i.e. When an external destabilizing factor is applied to it, the mini shield begins to deviate from the initial direction of penetration, continuing its movement in a new direction.

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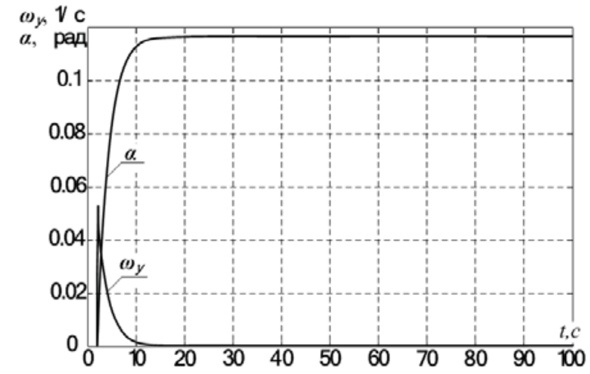

Figure 2: Graphs the change of the angular velocity and the angle of rotation of the mini shield during displacement of the point of the resultant force application of the pushing hydraulic jacks

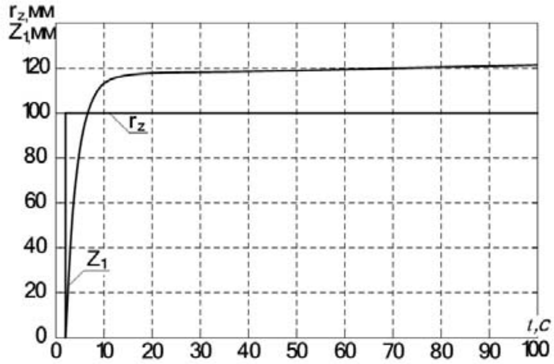

Figure 3: Graphs of the changes of the coordinate of the knife point of the mini shield and the radius vector of the point of application of the resultant force of the pushing hydraulic jacks

INVESTIGATIONS OF THE LASER SYSTEM FOR MONITORING THE POSITION OF THE SHIELD

The shield is guided along a given trajectory by means of a laser beam. Figure 4 presents the model of the module of the operator, compiled in a specialized software package of CAD ISIS Proteus, which includes the models of electronic components, with the possibility of adjusting their parameters. The model consists of transfer functions and elements describing: the loss of optical power of laser radiation in the atmosphere (ATMOSFERA1), the characteristics of the phototransistor element (FD_1, FD_2, FD_3), the load resistance (NAGRUZKA), the transmission factor of the amplifier (PREDUS2), the bandpass filter of the second order (POLOSFILTR2), A threshold device (TRIGGER2), a microcontroller (PROCESSOR2), switching elements with closing (1NO, 3NO) and breaking contacts (2NC, 4NC), digital signal level matching elements (K3, K4), and interference sources (f1, f2).

The study of the system is divided into several stages:

- study of the accuracy of determining the coordinates of the center of the laser beam as a function of the step of the photodetectors in the matrices and the diameter of the laser beam;
- investigation of noise immunity of the system under external illumination of photodetectors by optical radiation of various frequencies and powers;
- verification of the reliability of data transmitted to the operator's computer.

The accuracy of the determination of the coordinates was studied with the following parameters: the step of the photodetectors is 10, 15 mm; diameter of the laser beam 17, 50 mm. The movement of the mini shield (photodetector device) was simulated in such a way that the laser beam of the direction detector described on the tail photodetector matrix a circle with a radius of 53 mm, centered at the intersection of the symmetry axes of the matrix, and a straight line running along the diagonal of the matrix. As a result of the research, a series of graphs is obtained, an example of one of which is shown in Figure 5, the dotted line shows the permissible limits of deviation of the coordinate measurement ± 5 mm.

To check the accuracy of the system's operation for different parameters, an analytical calculation of the arithmetic mean $\bar{x}$, absolute Δx, mean-square value S and root mean square error of the arithmetic mean $S_{\bar{x}}$ errors was performed for each graph. The calculated errors for the shown in Figure 5 graphs were: $\bar{x}$ = 1.37 mm; S = 0.97 mm; $S_{\bar{x}}$ = 0,069 mm; Δx = 0.1359 mm. The average relative error was ε =2,34 %. The maximum absolute error during movement was 4.53 mm. When visual analysis of graphs and analytically obtained values is established that with a step of 10 mm photodetectors and a laser beam diameter of 17 mm and more, the system determines the coordinates with an error within the specified limits. At a step of 15 mm photodetectors and a beam diameter of 17 mm, in some positions of the laser beam there are "dips", i.e. on the matrix there are no illuminated photodetectors. When the diameter of the laser beam is increased to 50 mm, the "dips" disappear, the arithmetic mean, mean square and mean-square errors of the arithmetic mean error are within the permissible limits, but it can be seen from the graphs that in some points the absolute error exceeds ± 5 mm, which is unacceptable by technological Requirements, like and "failures". Thus, for a stable determination of the spatial coordinates of a mechatronic mini shield with an accuracy of ± 5 mm, it can be recommend the design of photodetective matrices with a 10 mm element pitch and a minimum diameter of a laser beam of a 17-20 mm setting.

The creation of effective optomechanical devices for monitoring and controlling the movement of mechatronic shields for the construction of mini tunnels operating in the atmosphere of a tunnel is impossible without taking into account its effect on the properties of laser radiation.

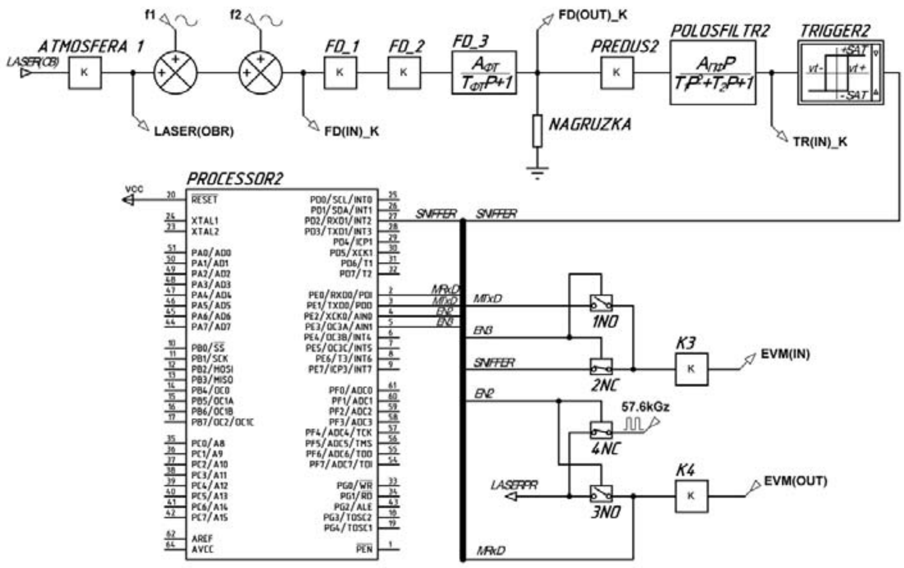

Figure 4: Model of the operator module

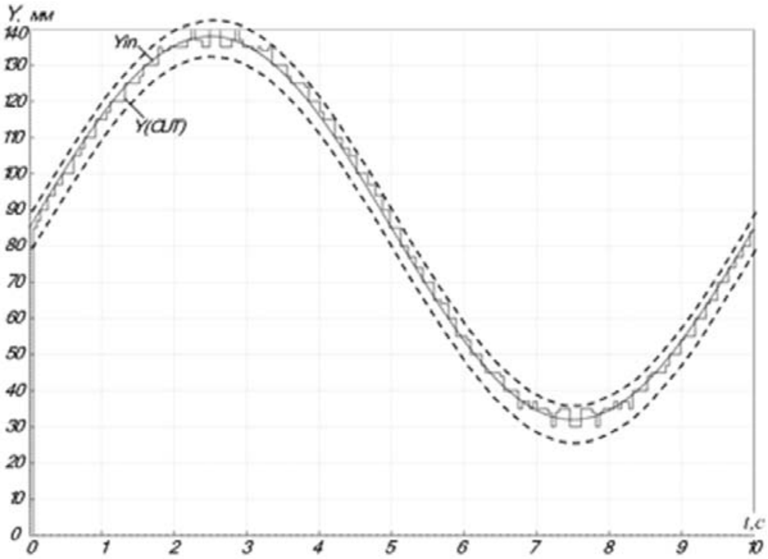

Figure 5: Graphs of the change of the given Yin and the measured Y(OUT) coordinates at the step of the photodetectors of 10 mm, the diameter of the laser beam of 17 mm

The main influence of the atmosphere reduces to a decrease in the power of optical radiation recorded at a distance from the source, due to the effects of scattering and absorption on solid and liquid particles in it in a suspended state. The total transmittance of coherent radiation by an atmosphere of a mini tunnel can be represented as $\tau_{атм}(\lambda) = \tau_{п}(\lambda) \cdot \tau_{р}(\lambda)$.

To calculate the absorption coefficient of radiation in the atmosphere, with only water vapor content, Elder and Strong proposed the formula: $\tau_{п}(\lambda) = t_0 - k_1 \cdot lg\delta$ where t_0, k_1 are constants for the considered spectral region, δ is the thickness of the precipitated water. The coefficient $\tau_p(\lambda)$ takes into account the scattering by water vapor and solid particles and is determined by the formula: $\tau_p(\lambda)=\tau_в(\lambda)\cdot\tau_m(\lambda)$.

The transmittance of the radiation $\tau_в(\lambda)$ with sufficient accuracy can be determined by the empirical dependence of the following form: $\tau_в(\lambda) = (\tau_{р.э.})^{L/1,83} \cdot 0,998^{(\delta-17)}$, where L is the path traveled by the radiation. The transmittance of monochromatic radiation $\tau_m(\lambda)$ is determined by the Bouguer formula: $\tau_т(\lambda) = e^{-[0,83\frac{NA^3}{\lambda^4 \cdot 10^{-3}}+\frac{3,9}{S_M}\left(\frac{\lambda}{0,55\cdot 10^{-5}}\right)^{-0,585\cdot\sqrt[3]{S_M}}]\cdot L}$, where N is the density of scattering particles, A is the cross-sectional area Scatterers, λ - radiation wavelength, S_M - meteorological visibility range.

In addition to the atmosphere, the power of the laser radiation influenced by the photodetectors is affected by its divergence. The power loss can be estimated from the formula: $P_R = P_т \frac{A_T A_R/\lambda^2 l^2}{\lambda^2 l^2}$, where P_R is the registered power; P_t - power of the laser source;

A_T is the effective aperture of the transmitter; A_R is the effective aperture of the receiver; λ is the wavelength of the laser radiation; l is the distance between the receiver and the radiation source.

As a result of the study of the total transmittance, with different initial data, graphs were obtained showing that the laser radiation power recorded at a distance from the radiation source decreases exponentially with distance from it, and the intensity of the power decrease depends on the meteorological visibility range [02].

CONCLUSIONS

As a result of the work done, it was established that the developed system can be used to determine the spatial coordinates of many mobile objects with the required accuracy and dynamic range of coordinate measurements, and also to exchange information with the equipment installed on them. The device can be used both for the construction of mini tunnels and for the construction of large-diameter tunnels. As a result of the tests it was established that the system fully meets all the requirements for accuracy of determining coordinates, speed of information exchange, noise immunity and range of functioning.

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