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Multimode control for optomechanical scanners with elastic links

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Abstract. The paper deals with the issues of control for optomechanical scanners with elastic links. Restrictions of various control laws in the solution of problems of stabilization, positioning, program movement are resulted. The expediency of using multi-mode control to improve the quality of optical scanning is shown.

1. Introduction

The specificity of the tasks of reading, documenting and recording graphic information determines the variety of optical scanning modes. Thus, line-by-line scanning of rectangular shape is realized by oscillatory movements along two mutually perpendicular axes. Scanning of the round-shaped field can be carried out by spiral and rosette trajectories, which are realized by means of modulated harmonic effects on the actuator of the scanner at each coordinate. Optomechanical scanners allow to obtain high informational and light characteristics essential for a number of applications [1]. Increased accuracy requirements for scanners determine the need for control systems with appropriate measuring transducers.

Among the optomechanical scanners can be identified a group of devices, that are characterized by the presence of pronounced elastic links. Such connections can be fundamentally incorporated into the device, such as galvanometers on extensions, or MEMS-scanners torsion type, or inevitably manifest themselves in mechanical design of deformable elements with elastic properties. A variety of scanning tasks makes it necessary to choice the control laws that implement the information capabilities of the scanner. In this regard, the article deals with the issues of multi-mode control for optomechanical scanners with elastic links, as well as possible structural implementation of control systems.

2. Linear approach and its limitations

A two-dimensional single-mirror optomechanical scanner with magnetoelectric actuator for high-precision reading and recording of graphic information is a plant in which the elastic properties are related to the elasticity of the current frame and the conditions for fixing it to the mirror [1]. Scanner studies have shown a complex multimode nature of these links. The dynamics of the scanner depends on the stiffness of the actuator, and its model with concentrated parameters can be described by a seventh-order differential equation, obtained on the basis of Lagrange equations of the second kind and magnetoelectric interaction equations [1]. The scanner model simplified for practical estimations for each coordinate can be represented by two successive oscillatory links and described by the angle-voltage transfer function:

$$W_{sc}(S) = \frac{\varphi(s)}{U(s)} = \frac{K_{sc}}{\left[T_1^2 S^2 + 2\xi_1 T_1 S + 1\right]\left[T_2^2 S^2 + 2\xi_2 T_2 S + 1\right]}. \quad (1)$$

Here, $\varphi(S)$, $U(S)$ - operator expressions of the angle of rotation of the mirror and the control voltage; K_{sc} – transmission coefficient of the scanner; S - complex variable. The first low-frequency oscillatory link (T_1, ξ_1) reflects the presence of the gravitational moment in the imbalance of the moving part of the scanner, and the second oscillatory link (T_2, ξ_2) reflects the elastic properties of the drive frame.

The design of the scanner provides for the presence of an interference sensor of angular deviations of the mirror in two coordinates with a sensitivity of 0.1 angular second in the range of up to two tens of angular degrees. The discrete type of sensor makes it possible to create a system for controlling the position of the mirror in space, to ensure its stabilization and movement with an error allowed by the measuring device.

Typical modes of operation of the scanner are fast transition from one fixed position to another, program modes of continuous scanning of a given surface or motion along a given trajectory with a maximum speed, which requires a coordinated movement of the scanning element in two directions. The modal control of such an object is problematic. In addition to the measurement of state variables, even with a significant difference in the time constants of the oscillatory links, among the limitations of the method include high gain and control signals that switch the system to nonlinear mode.

Proportional control of the scanner with elastic links, using the interference feedback on the position and stabilizing feedback on the speed can be performed according to the scheme in figure 1. It reflects the functional elements of the system: the object of control - a scanner with a transfer function $W_{sc}(S)$; power amplifier with a gain coefficient K_{is}; interference sensor with the transmission coefficient K_{da}; digital comparator and digital-to-analog converter with the transmission coefficient K_{da}; speed sensor with the coefficient K_{ss}. The channel of the combined control for formation of the compensating influence is described by the element with transfer function $W_{cc}(S)$.

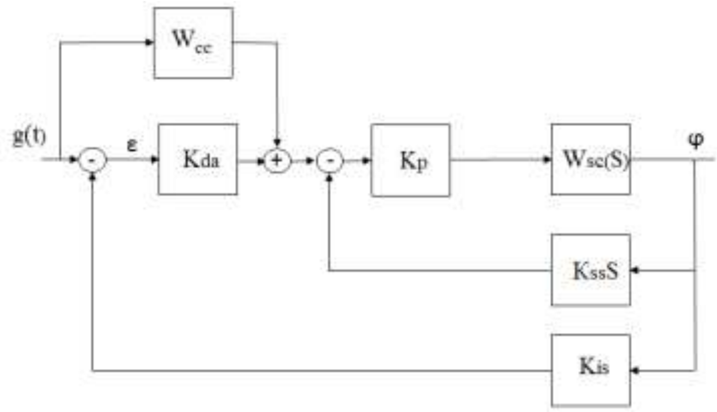

Figure 1. Block diagram of the scanner control system with proportional control law.

The frequency method of synthesis of the linearized control system of the scanner on the given index of oscillation of the closed system establishes forbidden areas for phase-frequency and amplitude-frequency characteristics of the open system near the cutoff frequency [2]. With regard to the model of linearized control system with deep speed feedback in figure 1, the condition for obtaining a given oscillation index M imposes restrictions on the parameters of the elasticity link and the total gain of an open at the angle loop K

$$T_2 \le \frac{1}{K}\frac{M}{M+1}2\xi_2 \tag{2}$$

Modelling and experiments with a real plant have shown that the behavior of the closed-loop system in dynamic mode approximately corresponds to its description in the form of an equivalent oscillatory link, the parameters of which depend on the properties of the elasticity of the scanner. An effective means of improving the performance of the system in linear modes is a combined control. An additional manipulated variable on the compensation channel, proportional to the derivative of the input, allows to speed up the transition process and thereby reduces the maximum dynamic error. For the scanner with parameters T_1 =0.07c, ξ_1 =0.4, T_2 =0.0005c, ξ_2 =0.1 the efficiency was 1.4 [3].

A means of expanding the dynamic capabilities of optomechanical scanning systems is the optical correction associated with the use of an additional low-inertia corrective deflector included in the scheme figure 2.

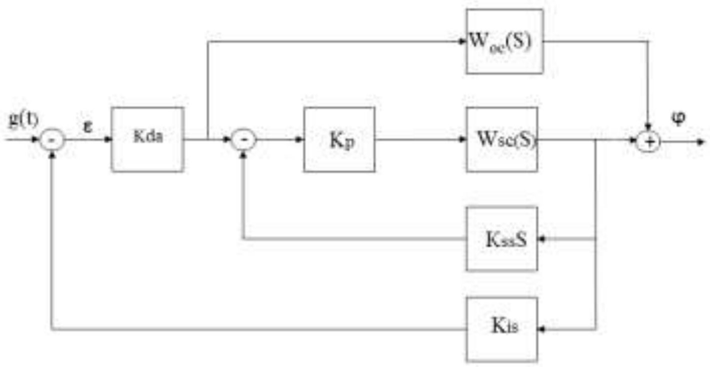

Figure 2. Block diagram with additional corrective deflector.

The additional deflector, without reducing the resolution of the entire optical scheme of the scanning spot formation, must compensate for the dynamic errors of the scanner control system. For effective correction, the time constant of the correction link should be significantly less than the electromechanical time constant of the main scanner. In the case of the task of creating a microraster, the formation of an additional control action synchronized with the motion along the line is required. However, the deflector, a built-in scanning system, introduces additional non-linearity associated with angular limitation.

3. Nonlinear regime

The discrete nature of the information retrieval of the interference sensor determine the fundamental non-linearity associated with the further digital-to-analog conversion. Increasing the gain in order to increase performance may lead to a self-oscillating mode, the parameters of which are determined by the linear and nonlinear parts of the system. In the analysis by the harmonic linearization method, the consideration of non-linearity as non-hysteresis allows considering only the in-phase component of the first harmonic at the output of the nonlinear element. The expression for finding the frequency of self-oscillations in the given block diagram figure 1 has the form.

$$\omega_a = \sqrt{\frac{2\xi_1 T_1 + 2\xi_2 T_2 + K_p K_{sc} K_{ss}}{2T_1 T_2(\xi_1 T_2 + \xi_2 T_1)}}. \tag{3}$$

In this case, the expression for finding the amplitude of self-oscillations A by the known coefficient of harmonic linearization $q(A)$ can be written in the form

$$q(A) = \frac{(T_1^2 + T_2^2 + 4\xi_1\xi_2 T_1 T_2)\omega_a{}^2 - \omega_a{}^4 T_1^2 T_2^2 - 1}{K_p K_{sc} K_{is} K_{da}}. \quad (4)$$

Additional nonlinearities available in the system and in the scanner increase the amplitude of self-oscillations. The described control law makes it possible to obtain for the scanner with the given parameters a stabilization in the self-oscillating mode with an amplitude of 1-2 units of the interference sensor.

The choice of control signals is contradictory. On the one hand, they must meet the requirements of permissible self – oscillations, and on the other-the requirements of the defined speeds of movement. The increase in performance can be achieved through the use of systems with variable structure including a linear combine control system and relay control system (figure 3). Initial phase of motion is performed by acceleration, by feeding to the input of scanner relay action U_p. In the moment the achievements of the extremum of the error the relay system switch off and included a system of combined control, which realizes minimum steady-state error in speed. The equation of the control system for the rotation angle of the scanning element at the initial stage of the transition process can be expressed as

$$(T_1^2 S^2 + 2\xi_1 T_1 S + 1)(T_2^2 S^2 + 2\xi_2 T_2 S + 1) \quad \varphi(t) = K_{sc} U_p \quad (5)$$

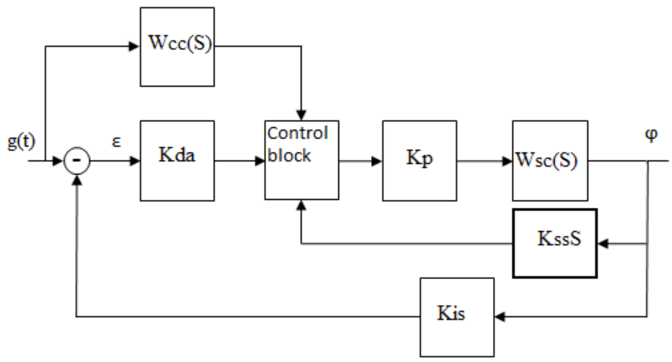

Figure 3. Block diagram of a system with a variable structure.

The equation of the system with respect to the angle of rotation of the scanning element in the combined control takes the form

$$[(T_1^2 S^2 + 2\xi_1 T_1 S + 1)(T_2^2 S^2 + 2\xi_2 T_2 S + 1) + K_p K_{ss} K_{sc} S + K_{da} K_p K_{sc} K_{is}]\varphi(t) = K_{sc} K_{da} K_p g(t) + $$
$$+ K_p K_{sc} W_{cc}(S) g(t). \quad (6)$$

The parameters of the correction link $W_{cc}(S)$ of the combined control system are selected from the condition of minimum steady-state error. In the transient process of testing the input $g(t) = \upsilon t$ the system error has a minimum, which can be adjust the system by the value U_p . It should be noted, that the maximum dynamic error was twice as much during the testing of this set point by a conventional combined system. Increasing the rigidity of the scanner allows not only to increase the gain of the system operating in a steady state, but also to obtain much larger control signals U_p in the transient mode.

4. Quasi-optimal positioning mode

Elastic links have a significant influence on the relay control modes, including the mode time-optimal control. The presence of the second oscillatory link greatly complicates the switching function. The number of intervals of constant sign of control actions and their duration depend on the initial state and the resonant frequencies of the scanner. The use in the positioning system of a simple control algorithm: "half way - acceleration, half way - braking" with a maximum acceleration because of the difference of real transfer function from the transfer function of double integrator leads to either overshoot or incomplete testing of the given move.

Functional diagram of the quasi-optimal scanner control system is shown in figure 4.

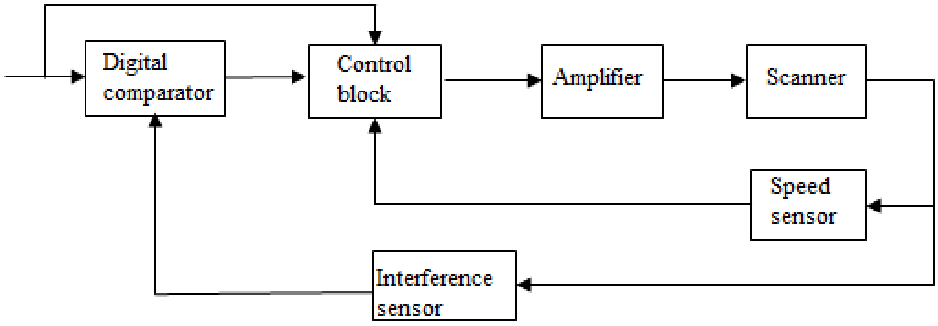

Figure 4. Functional diagram of the quasi-optimal control system.

The control block performs the "acceleration-braking" mode with switching of control on the half-way, and also includes a stabilization system when executing the corresponding conditions. Error of positioning of a relay system can be reduced by the stabilization system. A system with proportional control law can be considered as the stabilizing system. In this case, the positioning time t_{tp} consists of two components: time of movement in the relay mode t_r and the time t_{st} for stabilization of the scanner: $t_{tp} = t_r + t_{st}$. During the joint operation of the positioning system and stabilization system should be established $t_{tp} = \min(t_r + t_{st})$. Achievement of conditions of not exceeding by absolute values of an error on position and speed of certain sizes is used for establishment of areas of work of system of stabilization. In accordance with the functional diagram was simulated teamwork relay system and stabilization system for different values of displacement and different conditions for the activation of the stabilization system [4]. With reduction of speed at which turns on the stabilization system, the quality of the process improves. The stabilization system may be in the region of nonlinearity in the time of connection for large values of error and derivative of the output signal. At constant conditions of switching and displacement values the changes of the relay signal have a significant influence on the values of state variables at the time of the disconnect relay and as a result, achieve different times of the transients. The speed limit area must take into account the amount of displacement, as it affects the values of the output signal derivatives.

The area of operation of the stabilization system for a given error should in this case also be regulated. On the one hand, it is desirable to reduce the size of the area of stabilization, and with another - increase with increasing displacement, relay signal and increase the time constant of the second oscillating link.

Reduction of residual errors is also possible by changing the moment of switching the relay element or change the value of the braking signal. Selection the area of the inclusion of the stabilization system and the magnitude of the movement should be linked to the residual values of the state variables in which stabilization system is not yet in the region of significant nonlinearity.

5. Adaptive control

In the operation of control systems scanners have a variety of disturbing effects of complex nature, which leads to uncertainty of structural and parametric description of these systems. In optomechanical scanners, a number of coefficients and characteristics, for example, determining elastic links, viscous internal friction, viscous and dry friction of external forces, nonlinearities due to the design, are difficult to determine. In multi-dimensional scanners can occur mutual influence

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channels. Taking into account these effects is associated with the use of cumbersome calculation formulas, with the complexity of the mathematical model of the scanner or scanning system as a whole, with difficulties in its application for engineering calculations. The errors of scanning systems in some cases tend to be reduced to an acceptable level due to the precision optomechanical part, which creates additional difficulties associated with the adjustment and operation of the entire system. The incompleteness of information about the properties of scanners, elements of devices and control systems of scanners, increasing the requirements for the accuracy of positioning and reproduction of motion paths lead to the need to consider more complex control laws. Adaptive control system of torsion micro-mirror with electro-static drive and capacitive angle sensor is given in [5]. The system is made according to the scheme with a tunable plant model (figure 5). The self-tuning controller generates control actions based on feedback signals, estimator and input signals and adjusts its setting in real time. The model of the scanner with torsion suspension is described by the second order differential equation.

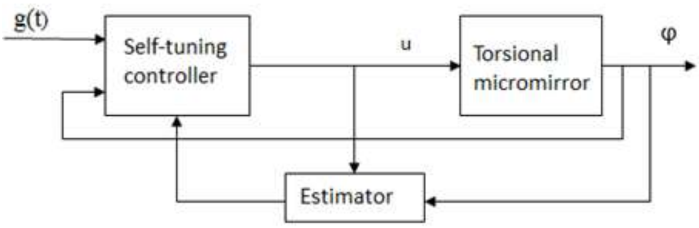

Figure 5. Functional diagram of adaptive control system micro mirror.

The results of modelling and experiments have shown the effectiveness of the adaptive control algorithm based on the quadratic Lyapunov function in position control and tracking, certain advantages over other regulators in terms of self-tuning in real time [6]. The system allows to compensate imperfections of the scanner and to reproduce the trajectory of the torsion mirror more accurately. As the order of equations describing the control object increases, the adaptation process becomes more complicated. In this regard, it is of interest to choose the most suitable structures for the control, algorithms and evaluation of the accuracy capabilities of adaptive control for other types of scanners with elastic links in real conditions.

6. Conclusion

The variety of tasks of high-precision scanning necessitates the use of multi-mode control, which is a means of adapting the scanning device to the scanned field, allows to realize the information, light and dynamic capabilities of the scanner. Elastic links of scanning devices complicate the tasks of high-precision stabilization and control. Combined relay-linear control allows to increase the speed of positioning and the response to linear input.

References

[1] Petrakov A V and Vyskub V G 2008 *High-precision television reading machines* (Moscow: Energoatomizdat)
[2] Besekersky V A and Popov E P 1966 *Theory of automatic control systems* (Moscow: Science)
[3] Vyskub V G, Zadernyuk V B, Mikheev V P and Savel'ev V I 1981 Analysis of combined control system of laser-mirror scanner. *Journal of Instrument Engineering* **9** 29-35
[4] Vyskub V G 2005 Control system optical-mechanical scanner with magnetoelectric actuator *Journal of Instrument Engineering* **2** 68-72
[5] Liao K-M, Wang Y-C, Yeh C-H and Chen R 2005 Closed-loop adaptive control for electrostatically driven torsional micromirrors *J. Microlith., Microfab., Microsystems* **4(4)** 041503
[6] Algreer M and Mohammad T M 2016 Real Time Self-Tuning Controller for Position Control of DC Motor System using Pole-Placement Technique *International Journal of Computer Applications* **155(3)**