Maximal amplitude of the frame at external action Q is determined by the expression

$$B = \frac{h}{\sqrt{(k^2 - p^2) - 4n_1^2 p^2}}, \qquad (10)$$

where k is the natural frequency of the frame, p is the frequency of external action.

It follows from the expression (10) that the larger the amplitude of the external mechanical action (h in numerator) the larger frame vibration amplitude with lidar but the larger damping coefficient of viscoelastic support n in denominator the less frame amplitude at external vibration action.

Selecting the corresponding constructive values k, p, n, l, J, c, P (expressions 7, 10) the frame vibration amplitude in the range of idle revolutions of car motor is possible to reduce practically to zero.

Conclusion

The technology of lidar vibrostabilization problem is analytically justified that allows minimizing the vibration amplitude of its aiming line in operating mode. It is achieved both by setting up viscoelastic shock absorbers and varying the parameters of mechanical system «Lidar radiator-lidar basis-automobile»: inertia moment, differences of natural and forced vibrations, damping coefficients, construction stiffness, pendulosity value.

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LARGE-FORMAT LASER RANGE

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New principle of large format scanning laser range construction for mobile object navigation realized on the basis of piezoelectric drive of laser beam inclination control has been suggested. Optimal drive parameters and laws of controlling range laser beam scanning were determined. Limiting angular format by azimuth coordinate (the most important one for navigation of water and ground mobile objects) up to hemisphere size is 180°. The proposed principle is approved in adaptive television automatic system, means of control and diagnostics of laser beam state at stochastic influence.

In many tasks solved in measurement technology, radiolocation, astronomy, optical communications, location, orientation, navigation and many other one of the problems is a support of high resolution and accuracy of defining mobile object coordinates in wide field of view of devices and systems [1–4]. The possibilities of applying in laser systems the adaptive optics elements for precision control of radiation characteristics carrying information about spatial field and objects in it are attractive. Piezoelectric converters «electric signal – force action» are used as executive actuators of microcontrol for adapting systems and controlling wave front of laser beams. The experience shows that piezoelectric actuators are rather effective in the adaptive optical engineering. Their advantages are fully determined by the degree of complexity of control and STC algorithms accepted in the devices that allows decreasing field structure deformations caused by the factors of random and active disturbance reaction on the final result of system operation [1–9].

Piezoelectric actuators having rapid response and small dimensions are applied for picture stabilization in scanning microscopes and microtome vibroknives besides laser, thermal imaging, location, navigation and adaptive engineering [1–9]. Their further development as the efficient elements of radiation control is restrained by narrow scanning range. In spite of variety [3, 4] of actuator constructions the problem of developing the optimal structure of laser beam control actuator could be hardly considered a solved one or close to completion. Scanning actuator of laser cross section beam as the element of control system of ship navigation [2, 7] has individual peculiarities due to the necessity of high accuracy at coordinate determining for controlling mobile object in real time in wide azimuth region of its place for navigation of media on curved paths.

The original scanning actuator of laser cross section beam [5] as the element of navigation system of mobile object in wide angular range of coverage with laser beam close in dimension to hemisphere in azimuth region is described in the given paper. The variants are analyzed and laser cross section actuator is optimized for improving its technical characteristics, the results of studying the application of one of its modifications in model turbulent medium are given.

The actuator structure is presented (Figure) in the variant of laser He-Ne beam inclination partitioned by each of coordinate control axes. The actuator is made in the form of two flexural elements – 1 and – 2 cantilever separated in space, fixed in the barrel – bearing – 3 with one of the end. Control object – mirror (flat substrate – 4 with reflecting layer – 5) is attached to the free ends of flexural elements at two elastic link-suspensions – 6. Mirror attachment in two points is hinging – 7 and does not limit bimorph end movement in space. Application of flexural elements is stipulated by the condition of achieving maximal advantage in actuator response. Hinging – 7 (7-1 and 7-2) of control object – flat mirror gives large angular deviations.

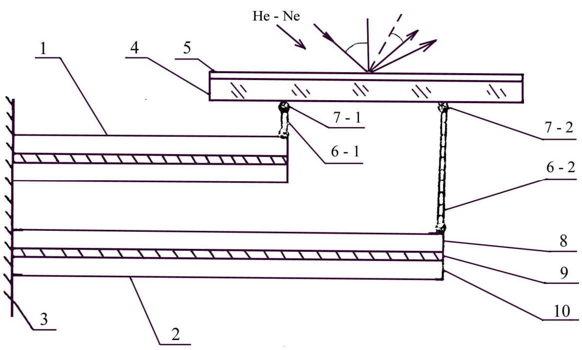

Figure. *Block diagram of bimorph actuator*

At slight angular mirror deviations (about degree units) mirror suspension links may be made on the basis of plastic-elastic materials (rubber resin, rubber, polyimide). Rubber-polymer material obtained on the basis of certain ratios of butyl and ethylene-propylene rubber was applied.

Both elements – 1 and 2 of the actuator are glued in such a way that at control signal injection to the inner – 8 and outer – 10 piezolayer electrodes – 9, layer deformations equal in magnitude but oppositely oriented respect to gluing plane occurred in bimorph piezoelectric plates. They condition the occurrence of transverse forces resulting in element bending vibration. In essence, two variants of gluing plates (with coincident and opposite directions of polarization vectors) and two connection schemes of control signals to element electrodes are possible for achieving the required bending type. Bimorph elements – 1 and 2 are practically identical. The required shift of elements relative to each other is supported by echelon form of bearing – 3. At flat form of bearing – 3 the elements of various length are used and matching the behavior dynamics identity is supported electrically fitting amplification coefficient of control signals by these elements.

Depending on purpose and spatial scanning algorithm (raster type) two variants of schemes of control signal injection to the pair of elements and schemes of elements positioning, resulting in binding of element pair, composing actuator are possible [5, 6]. In the first case the actuator gives linear mirror shift along one of coordinate axes. In the second case there is the actuator of angular deviation of control object – mirror.

The purpose of optimization of actuator controlling laser cross section beam is in achieving maximal response, conversion conductance and wide dynamic range of beam control. The ratio of transition of flexural element free end to control signal should be maximal at high accuracy of setting mirror (and laser beam) as the control object, response speed, mechanical strength and reliability of actuator. Transition of bimorph free end is determined by element deformation: $S_1=d_{31}E_y+S^E_{11}T_1$, where: d_{31} is the piezoelectric modulus; E_y is the strength of applied electric field; S^E_{11} is the elastic constant (compliance); T_1 is the elastic mechanical stress.

In general case, ξ transition of flexural element end of the actuator is nonlinear function of the applied signal U_y of actuator control: $\xi=f(U_y)$. Nonlinear static performance $\xi=f(U_y)$ with hysteresis loop is characteristic for bimorph elements. The given control actuator allows obtaining mirror angular shift determined by doubled ratio ξ of the shift of flexural element free ends to ℓ_3 centre-to-centre distance of mirror fixing points to them $\alpha=2\xi/\ell$. In particular case of link fixing to the mirror extreme edges this distance is comparable with mirror geometries. The mirrors (5×5 and 8×5 mm^2) were used.

The shift of bimorph free end depends linearly on the value of control signal U_y in the capacity of which the sweep signal may serve [10] or in the case of active object guidance the signal of controlling beam position formed by electron system of laser cross-section [1, 10]. Resultant angular displacement of the mirror by the actuator along the selected (X or Y) coordinate axis amounts to the size of order:

$$\alpha \sim 2K_{\Pi}d_{31}\ell^2U_y / a^2\ell_3.$$

Here: K_{Π} is the coefficient depending on the type of material, dimensions, discreetness and a number of other element parameters; d_{31} is the lateral piezoelectric modulus; ℓ and a are length and thickness of the elements correspondingly. In general case, $\ell_1\neq\ell_2$, $U_{1y}=U_{2y}$ but ξ_1 and ξ_2 may be identical: $\xi_1\equiv\xi_2$. Though, the fulfillment of this condition is not obligatory for the actuator of beam angular deviation. Q-factor of the actuator Q is determined by the decay time τ_e of the natural vibration by the frequency f_0 ($\omega_0=2\pi f_0$) in e times:

$$Q = \omega_0\tau_e / 2.$$

Rational choice of mechanical scheme of force transfer and excluding of random influence on control element – mirror and beam – are the important factor of supporting the required accuracy of beam controlling. By means of simple conversions it is possible to show that the angle of mirror rotation amounts to

$$\alpha_0 = \sum_{i=1}^{2} \mathrm{arctg}(K_{yi}\, l_{xi}^2 / \Delta x), \quad (i = 1,2),$$

where K_{yi} is the coefficient of proportionality, l_{xi} is the length of flexural elements; Δx is the distance between the points of mirror fixing. The efficiency of gain by the angular deviation of this type of actuator of mirror control, in comparison with single piezoelectric element in the actuator of type [3], amounts

$$\chi_\alpha = (m_e^2+1)/2a_e m_e(1-m_e),$$

where $m_e=l_{x1}/l_{x2}$ is the ratio of flexural elements lengths in the actuator ($l_{x2}\geq l_{x1}$); $a_e=l_1/l_{x1}$; l_1 is the length of the element in single actuator. It follows from the expressions that for the concrete comparison (at $l_{x1}=l_1$ or $a_e=1$) the maximal gain equals to $(m_e^2+1)/2m_e(1-m_e)$ occurs. At random a_e and m_e the gain is easily determined. The ratio of frequencies f of the first resonance for the compared periods amounts to:

$$\chi_f = a_e^2 m_e^2.$$

These expressions allow searching for optimal parameters of control actuator meeting the fulfillment of two conditions: $\chi_\alpha>1$ and $\chi_f>1$. Thus, it is possible to develop the actuator supporting simultaneously the gain both by the angle of deviation and spatial resolution, and by response speed (increasing first resonance frequency) of space scanning with the beam. Optimal ratio of actuator parameters is found from the solution of inequality system:

$$\begin{cases} a_e < (m_e^2+1)/2m_e(1-m_e) \\ a_e > m_e^{-1} \end{cases}.$$

Solution region of inequality system is limited by the curves corresponding to the conditions $\chi_\alpha=1$ and $\chi_f=1$. Asymptotic dependence tendency (at $m_e\to1$) to ∞ does not accurately reflect actuator practical operation. In the range of $m_e\sim1$ the technique of mirror bounding influences greatly laser beam transfer.

To improve actuator characteristics different solutions may be used. For example: triangular elements application instead of rectangular ones in the actuator gives the growth of mirror angular shift in one and a half times ($\alpha_\Delta=1{,}5\alpha_\Pi$) at simultaneous expansion of operation area of amplitude-frequency characteristics. For triangular elements the frequency characteristic area of actuator, free of mechanical resonance, is expanded twice for understressed actuator and in π times for greatly stressed actuator i. e. when load mass of control element is comparable with actuator element mass.

The actuator practically produced on the basis of piezoceramics TsTS-19 gave mirror angular shifts in the range of ±1,5° while turbulent blurring and vibration of image at real paths, for example, in astronomic telescopes, amount the value which is three order less.

The dynamic properties of scanning actuator of cross section laser beam were studied by estimating real Q-factors of transient. In general case the transient of actuator and cross section laser beam assignment is asymmetrical vibration one and represents the sum of high-frequency vibration and direct components which are slowly changed. It is conditioned by the presence of real and complex conjugate roots of solving the equation of laser beam scanning actuator – the element of automatic control system. Practically cross section actuator as the control device of wave front inclination of laser beam represents a distributed vibration system with several degrees of freedom. Actuator transfer function in generalized view is the ratio of normalized power polynomial

$$\Phi = \frac{\xi(p)}{U_y(p)} = K\frac{B_m(p)}{A_n(p)} = K\frac{b_m p^m + \ldots + b_i p + 1}{a_n p^n + \ldots + a_i p + 1},$$

where K is the static coefficient of actuator transfer; $n>m$ and $n\geq2$.

In the case of control of laser beam scanning by a variable signal the transfer function of actuator has the form typical for vibration second order link

$$\Phi(p) = K/(\tau_0^2 p^2 + 2D\tau_0 p + 1),$$

where τ_0 is the time constant; $D=\omega/2Q$ is the relative attenuation constant. Accounting distributed character of the actuator controlled by the system allows using special methods of increasing stability and decreasing dynamic error in control loop. This method results in the synthesis of more complex devices and mechanisms of actuator control by laser beam position.

In scanning laser cross section the signal $U[\Delta Z(t)]$ is specified to the actuator. It is proportional to the magnitude of spatial values increment for changing laser beam position $\Delta Z(t)=Z_i(t)-Z_0(t)$ and equal the coordinate difference of the defined position $Z_i(t)$ relative to the coordinates of bearing $Z_0(t)$ – previous beam position in radiation space. The process of mirror – the control element of cross section laser beam – assignment to a current position $Z_i(t)$ with the help of mirror control actuator, for example, by the coordinate X of the plane $Z(x,y)$ occurs as a first approximation by the following dependence

$$x_i(t) = x_0(t) + \Delta x_i(t)\exp(-Dt)\cos(\omega t + \varphi),$$

where ω and φ are the circular frequency and phase of the control signal $U[\Delta x(t)]$.

Average value of the dimension of laser cross section beam controlled by the actuator is searched by integrating in the range of bimorph vibration period (0; $\tau_\delta\sim\tau_0$) with further normalization

$$\overline{x(t)} = \int_0^{\tau_\delta} x(t)p(t)\,dt \Big/ \int_0^{\tau_\delta} p(t)\,dt.$$

Here $p(t)$ is the symmetric weighting function meeting the condition $\int_0^{\tau_\delta} p(t)\,dt = \tau_\delta$. Vibration period of control element assignment to the specified new position is rigidly bound with resonant properties of actuator as vibration link of the system. The error of control element assignment to the specified position $[x_i(t)-x_0(t)]$ is searched from the above mentioned expressions (for $p_0=1$). Representing weighting function in the form of Fourier series $p(t) = 1 + \sum_{k=1}^{\infty} p_\kappa \cos\kappa\omega t$ (p_κ is the coefficient of Fourier series) we obtain

$$\overline{x(t)} - x_0(t) =$$

$$= \frac{\Delta x(t)}{\tau_\delta}\sum_{\kappa=0}^{\infty} p_\kappa \Big[\int_0^{\tau_\delta} \exp(-Dt)\cos(\omega t + \varphi)\cos\kappa\omega t\,dt\Big].$$

If we limit the accuracy of error computation at control element assignment with laser cross section actuator to the specified position by the members of the infinitesimal order D^2 then after integration and certain simplifications the error has the form

$$\overline{x(t)} - x_0(t) = \frac{\Delta x(t) D}{\omega} \sin\varphi \left(\sum_{\kappa=2}^{\infty} \frac{p_\kappa}{\kappa^2 - 1} - 1\right).$$

p_2=3 at which the weighting function has the form: $P(t)=1+3\cos 2\omega t$ meets the minimization condition of control error $[\overline{x(t)}-x_0(t)\rightarrow 0]$. Hence the average magnitude of the coordinate of control element position (mirror or laser beam) at step τ of interval ($\tau_\delta=n\tau$) of controlling laser beam inclination actuator amounts

$$\bar{x}_0 = \frac{1}{\tau_\delta} \int_0^{\tau_\delta} x_0(t)(1 + 3\cos 2\omega t)dt = x_0\left(1 + \frac{3}{2\omega\tau} \sin\omega\tau\right).$$

For clock control frequencies of actuator close to resonant ones ($\omega\tau$~0,5) and $\sin\omega\tau \sim \omega T$ and $\bar{x}_{0\varepsilon}=2{,}5x_0$. The conclusion follows from this that at clock control frequency close to the resonant one the amplitude of control object – a beam – transfer exceeds the required value in 2,5 times. The conclusion is confirmed by the behavior of amplitude-frequency characteristic of the actuator similar to [3]. In other words, at clock frequency of processing control signal of beam position by the actuator a lower stress of control signal and a lower coefficient of chain amplification are required because of the sensitivity increased about 2,5 times. It increases response speed, accuracy of control and stabilization processes of beam attitude position as well as control system stability in whole.

Dynamic accuracy of stabilization at assignment of cross section laser beam by the actuator may be increased using the second derivative of control signal of cross section beam position. Acceleration of changing the signal of control of laser beam position is proportional to the sum moment influencing the mirror $\alpha''(t) = \sum_1^i M_i(t)/I$, where I is the moment of mirror inertia – control object; $\sum_1^i M_i(t)$ is the sum of all moments influencing the stabilization object – laser beam including disturbing and stabilizing ones.

The additional signal proportional to the second derivative of control signal should be generated at the coincidence of signs of acceleration and rate of beam stabilization signal when the control object – mirror accelerates. Otherwise, the second derivative of control signal impairs the stabilization process of laser beam. Owing to the fact that the fall of additional signal after decreasing of mirror transfer acceleration to the specified value is carried out by a certain uniform (linear or exponential) dependence, not spasmodic, then the actuator smoothly attains the stabilization mode. The transient of mirror and laser beam assignment to the specified position becomes less vibrating. Using the second derivative of control signal only at acceleration stage at mirror transfer to the new position allows also increasing laser cross section speed of response. So at control signal injection to the control actuator of laser beam inclination of a step the mirror is assigned to the required position during the time equal $3\tau_\delta$ (τ_δ is the time constant of actuator). Using the second derivative of control signal at acceleration stage the mirror is already assigned to the new position at the first stage of the transient. In ideal case this gives triple advantage in speed of response at simultaneous increasing accuracy of beam position stabilization in a space.

The apparent disadvantage of piezoelectric actuator in laser cross section as a precision-scanning device is its susceptibility of noise vibration influence especially of that part the vector of which effects in the direction of least rigidity of flexural plates. The ideal variant of control actuator of mirror cross section was the variant based on the coincidence to the Newton's first law at which the mirror free hanging in the actuator and possessing a certain inertia moment would not be affected by external disturbance.

Vibration often has nonuniform spectral distribution with spikes at rotation frequencies of electromechanical devices and resonance frequencies of system separate joints. Upper bound of low-frequency spectrum of vibration effect is in the range of 60 Hz and more seldom it ranges to 300...400 Hz. Influence of vibration as well as load mass of beam control actuator – mirror condition the occurrence of inertia resultant forces – vibration one F_v and force of load pressure $F_н$ taken into account by bending moment $M=M_н+M_v$ determined by the ratios: $M_v=F_vl_v$ and $M_н=F_нl_н$. Here: l_v and $l_н$ are the distances from the appropriate points of force application to the bimorph. Force F_H takes into account not only the influence of mirror weight and the elements of its assignment but also spatial orientation of flexural elements and load element – mirror relative to the direction of gravity force vector. If inertia forces caused by vibration influence with acceleration a_V are uniformly distributed along the length of elements then for flexural element (with specific density ρ, width b_i, thickness a_i and length ℓ_i) we have: $F_V=(b_i\ell_ia_i)\rho a_V$ or $M_V=(b_i\ell_ia_i)a_V\rho\ell_i/2$.

Mirror acceleration is proportional to the square of vibration amplitude subject to spike amplitude superposition at frequencies of mechanical and electric resonance of flexural element and actuator elements. Linear vibrations of actuator are transformed into mirror angular oscillations of the same frequency due to unavoidable errors of mirror centre coincidence with the mass centre and limited rigidity of the construction. Inertia moment $I_з$ of the mirror tending to retain quiescent state resists to the moment of disturbing action. The inertia moment of mirror opposition to acceleration of forced oscillations a_V equals $M_I=I_зa_V<<1$. At mirror fixation in ball-and-socket joints the influence of vibration is partially damped to the mirror due to Coulomb dry friction in contact surfaces of joint spheres. The value of vibration damping may be controlled by the effort of cogging the sphere of joint inner finger by outer sphere. It should be taken into account that damping increase may result in growth of duration of mirror assignment transient into new state at clock control interval. When adapting a part of vibration spectrum is generally compensated in a closed circuit but the load inertia influence is remained.

Actuator and laser beam are controlled by vector scanning signal $\Delta Z(t,\tau)$ in the plane $Z(x,y)$ equals the difference of coordinates $\Delta Z(t,\tau)=\hat{Z}(t_j)-Z_0(t_i)$. Here $\hat{Z}(t_j)$ and $Z_0(t_i)$ are the magnitudes of coordinates of laser beam position at time points t_i and $t_j=t_i+\tau$, divided by delay interval during which the estimation of position is formed and beam actual distances are adjusted. Their change in the point of mobile object location represents random process generated by deformation of radiation picked up by the object pointed to the cross section. Presence of delay time at estimation and change of coordinates generates dynamic error of assignment of laser beam position relative to $Z_0(t_j)$ the coordinates of its real position in observation plane

$$\Delta Z_g(t,\tau) = \hat{Z}(t_j) - Z_0(t_i).$$

Estimation of dynamic constituent of coordinate error at beam assignment in actuator control signal of laser cross section may be presented in the form [1]

$$\Delta Z_g(t,\tau) = K_Z \sigma_Z [1 - \rho_Z^2(\tau)]^{1/2},$$

where K_Z is the coefficient depending on statistics of coordinate fluctuation distribution in the plane of laser beam estimation; σ_Z is the average square deviation and $\rho_Z(\tau)$ is the autocorrelation function of random drifts of laser beam centre of gravity. The form of the latter is determined by the properties of radiation propagation medium and instability of position of navigation object itself. For uncorrelated samples $Z(t_{i,j})$ K_Z=0,5. Dispersion of actuator control signal is determined as

$$\sigma[Z(t)] = 0,5\sigma_Z[\Delta Z(t,\tau)].$$

This dispersion estimate is unbiased if the samples of beam coordinates $Z(t_j)$ and $Z(t_i)$ are statistically independent. Presence of correlation between coordinate samples $Z(t_j)$ and $Z(t_i)$ results in the shift of estimation of average square deviation. Usually interval τ between adjacent samples of beam coordinate at estimation of navigation and adaptation object position is less than correlation window of beam position fluctuation for steady control of its aiming and compensation of these chance variations. In practice actuator control signal is the mixture of a regularly or slowly changing signal and random components. Correlation function of such mixture does not asymptotically tend to zero at increase of interval between the samples due to the influence of regular composition but the estimation error of average square deviation of control signal constituents multiple of frequency of beam coordinate samples occurs.

To estimate the influence of nonstationary, refraction trend of fluctuation of laser beam position the sampling interval of its coordinate values should significantly increase correlation window of samples $Z(t_j)$ and $Z(t_i)$. If one takes into account that fluctuation nonstationarity of laser beam front inclination is a slow process (spectrum is in the range of frequencies from 0 to 0,01 Hz) then one can expect that it does not particularly influence the accuracy of estimation of actuator efficiency in laser cross section.

The power of shift fluctuations conditioned by noncompensated part of random inclination of laser cross section beam with adaptation to stochastic influence of atmosphere effect – above water medium and wave height – of surface instability of navigation object transfer amounts to

$$P_\Delta = \frac{1}{T}\int_0^T \Delta Z^2(t,\tau)\,dt.$$

Presenting coordinate fluctuation of laser beam by Fourier series and limiting series decomposition of $\sin\omega t$ – constituent we obtain at first approximation the power of residual fluctuations of beam shift – actuator control signal in the form

$$P_\Delta = P_0(1 - \cos\omega_{cp}\tau),$$

Where P_0 is the average power and ω_{cp} is the average frequency of spectrum of beam residual random shifts conditioned by the medium of radiation propagation. Taking into account that really the frequency of beam coordinate sampling is much (in m times) higher than the average frequency of random transfer ($\omega_{cp}\tau$<<1) then the power of residual fluctuation of beam control signal as a fluctuation process of its shift to the specified position is simply to be defined

$$P_\Delta = P_0(1 - [1 - \omega_{cp}^2\tau^2]^{1/2}) \sim 10^{-m} P_0.$$

The examined actuator created for compensator of laser beam inclination in adaptive system may be also used in control systems of dynamic characteristics and control of mechanical structure parameters including control of current feed electrode position in the devices of contact welding of thin layers of corrosion-resisting materials similar to polymorphous zirconium alloys [11] as it possesses high time (~ ms), linear (~ fraction mkm) and angular (~10^{-6} rad) spatial resolutions in wide angular dynamic range.

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