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Study of microrobots operating in the mode of steerable resonance

Development and creation of new miniature actuators is an important task for many fields of engineering and medicine, particularly for creating inspection microrobots moving inside the pipes of a small diameter (2-10 mm). Analysis of the known actuators for microrobots has shown that it is the most efficient to use piezoelectric (ultrasonic) motors as they are the most energy-conserving and compact.

For creation of controlled microrobot movements it is necessary to provide possibility of independent control of its actuating elements that can be achieved by means of relative shift of their resonant characteristics. If excitation frequency of the elements is changed then movement direction will be altered because of vibrations asymmetry. Alteration of conditions of environment, which interacts with actuating elements, will lead to the shift of resonant characteristics. For detection of this shift and adaptation of microrobot to the uncertain environmental conditions it is necessary to introduce sensitive element. With the use of modern methods it is possible to deposit sensitive piezoelectric elements directly onto the actuating elements of microrobots and control these elements with special microcontrollers. The described concept of microrobot control can be characterized as a concept of “steerable resonance”.

The necessary condition of ultrasonic motor operation is creation of ellipsoidal trajectory of the stator points interacting with rotor [1, 2]. Complex trajectory of the actuating elements can be implemented by means of their formation in the shape of spatially-curved elastic bars [3, 4]. In this work we propose to use as actuating elements rectilinear elastic bars with artificially created local asymmetry, which can be introduced by means of local removal, attachment or plastic deformation of material. Possibility of application of such actuating elements for creation of microrobots should be additionally studied but we have obtained a number of interesting experimental and theoretical results in this direction. It is shown experimentally that three rectilinear bar elements with local asymmetry arranged onto the planar piezoelectric stator can be used for creation of controlled rotation of spherical rotor. In the previously developed prototype of such actuator controlled rotation was implemented by means of application of spatially-curved bars and application of rectilinear bars yielded no positive results. Effect of changing equilibrium shape of elastic bars with local asymmetry under the influence of flexural vibrations is experimentally shown and theoretically described. For theoretical explanation of this effect let us consider flexural vibrations of a bar with constant cross section, which has local non-homogeneity of material properties located asymmetrically relative to the bar axis (Fig. 1).

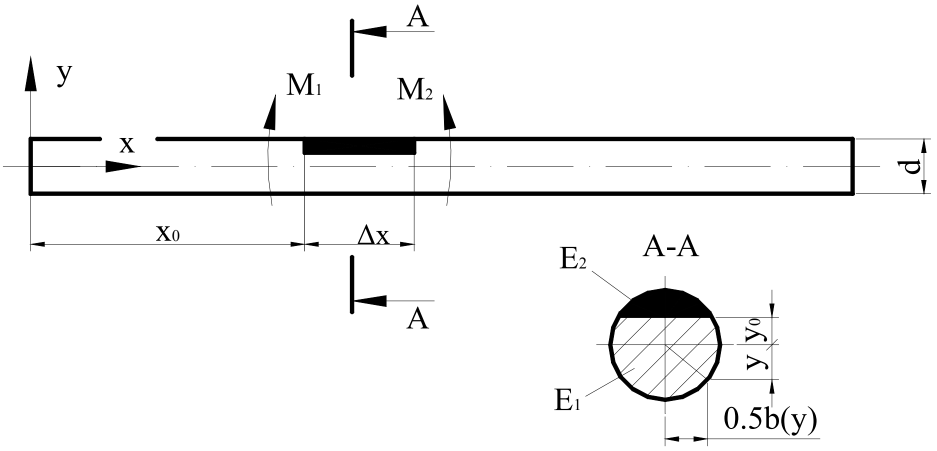

Fig. 1

Relative deformation in arbitrary point (*x*; *y*) of the bar for the moment of time *t* can be defined by relation

$$\varepsilon(x,y,t)=\varepsilon_0(x,t)-y\theta'(x,t),$$

where $\varepsilon_0(x,t)$ is relative deformation of the bar axis in the point (*x*; 0) for the moment of time *t*,

$\theta(x,t)$ is rotation angle of the bar cross section.

Bending moment in a cross section with local non-homogeneity of material properties is defined by expression

$$M(x,t)=E_1\int_{-d/2}^{d/2}\varepsilon(x,y,t)yb(y)dy+(E_2-E_1)\int_{y_0}^{d/2}\varepsilon(x,y,t)yb(y)dy=$$

$$=-E_1J\theta'(x,t)+(E_2-E_1)(S_1\varepsilon_0(x,t)-J_1\theta'(x,t)), \qquad (1)$$

where E_1 is elastic modulus for material of the homogenous part of the bar,

E_2 is elastic modulus for material of the non-homogeneity,

d is diameter of the bar,

$b(y)=\sqrt{d^2-4y^2}$ is width of the bar cross section at the level *y*,

y_0 is coordinate defining location of the non-homogeneity relative to the bar axis,

$J=\int_{-d/2}^{d/2} y^2 b(y)dy$ is centroidal moment of inertia of the bar cross section,

$S_1=\int_{y_0}^{d/2} yb(y)dy$ is first (static) moment of the non-homogenous part of the cross section,

$J_1=\int_{y_0}^{d/2} y^2 b(y)dy$ is centroidal moment of inertia of the non-homogenous part of the cross section.

In the expression (1) the first integral represents bending moment, acting in the cross section of the homogenous part of the bar, and the second one represents increment of bending moment related to the presence of the non-homogeneity. Value of the first integral does not depend on the value $\varepsilon_0(x,t)$ of relative deformation of the axis since integration of the odd relative to the variable *y* function $\varepsilon_0(x,t)yb(y)$ over symmetric interval gives zero. As the second integral is calculated over non-symmetric interval, which corresponds to the asymmetric location of the non-homogeneity relative to the axis, its value depends both on rotation angle of the cross section and on relative deformation of the axis.

If flexural vibrations of the bar have a period *T*, then after integration of the expression (1) over period of vibrations we obtain

$$\int_0^T M(x,t)dt=-(E_1J+(E_2-E_1)J_1)\int_0^T \theta'(x,t)dt+(E_2-E_1)S_1\int_0^T \varepsilon_0(x,t)dt\,. \tag{2}$$

If flexural vibrations are symmetric relative to the equilibrium position, then transversal displacements are described by the odd relative to the time function, i.e. $\eta(x,t)=-\eta(x,T-t)$. Longitudinal displacements in this case satisfy relation $\xi(x,t)=\xi(x,T-t)$, i.e. they are described by the even relative to the time function. Similar relations are satisfied for the derivates $\eta'(x,t)$ and $\xi'(x,t)$.

Let us consider dependence of the values $\theta'(x,t)$ and $\varepsilon_0(x,t)$, appearing in the equation (2), on the longitudinal and transversal displacements:

$$\theta'(x,t)=\left(arctg\frac{\eta'}{1+\xi'}\right)'=\frac{\eta''(1+\xi')-\eta'\xi''}{\eta'^2+(1+\xi')^2},$$

$$\varepsilon_0(x,t)=\sqrt{(1+\xi')^2+\eta'^2}-1.$$

It follows from the given relations that the function $\theta'(x,t)$ is odd relative to the time and integral from this function over period of vibrations is zero. The function $\varepsilon_0(x,t)$ is nonnegative and even relative to the time and integral from it over period of vibrations is non-zero. So right-hand member of the expression (2) is non-zero and bending moment has constant component since $< M(x,t) >= \frac{1}{T}\int_0^T M(x,t)dt \neq 0$.

If to consider a part of the bar with the length Δx, in the limits of which non-homogeneity is concentrated, then its ends will be loaded with constant components of bending moment defined by expressions

$$M_1 =< M(x_0,t) >= \frac{(E_2 - E_1)S_1}{T}\int_0^T \varepsilon_0(x_0,t)dt\,,$$

$$M_2 =< M(x_0 + \Delta x,t) >= \frac{(E_2 - E_1)S_1}{T}\int_0^T \varepsilon_0(x_0 + \Delta x,t)dt\,,$$

where x_0 is coordinate characterizing location of the non-homogenous part of the bar. In the case, when the values of the axis relative deformation on the ends of considered part are distinct, net moment $M_2 - M_1$ will be non-zero and this will lead to the appearance of constant component of the axis bending for the non-homogenous part of the bar. This means that non-homogenous part of the bar can be considered as specific elastic hinge, deformation if which results in the change of angle between the homogenous parts. Controlled movement of the bar with such elastic hinge which can be used in actuating devices of automatic control systems and also in precision actuators.

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