Active vibration isolation of nanotechnology equipment

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Abstract. The paper is concerned with the results of experimental studies of the parameters of transients during the operation of a high-precision drive based on a magnetorheological (MR) elastomer with a closed control system, which is also an active damper. In this paper, the authors showed the amplitude and frequency characteristics of the damper and vibration-isolating platform in semi-active mode and presented a model of outgassing from the near-surface layer of MR elastomer. The results of studies on the partial composition of gases released from the MR elastomer at the temperature 150℃ are given, depending on the pumping time.

1. Research of transients during the moving active damper

The miniaturization of devices and devices of micro and nanoelectronics and microsystem technology determine key requirements for minimizing the size of elements in integrated circuits and micromechanical components. Nanolocal treatment with ionic and electron beams, micro- and nanolithography, intermediate surface control are the main technological operations for the production of micro- and nanoelectronics and micromechanics products.

As an example, Figure 1 shows a high-vacuum scanning electron microscope (SEM) circuit. The SEM contains an electron-optical system (including an electron gun 1, a focusing system 2, a scanning system 3, a projection lens 4) providing the formation and scanning of an electron beam 5, a high-vacuum chamber 6, an active vibration isolation system 7 fixed on the coordinate table 8 sample 9 which reflects the flow of secondary electrons 10, the detector of secondary electrons 11.

Mechanical closed mounting system of the main SEM nodes, including nodes of the electron-optical system 1, 2, 3, 4, high-vacuum chamber 6, coordinate table 8, sample 9, secondary electron detector 11, has low rigidity and small resonant frequencies generated by these inertial elements. The resonant frequencies of the SEM are manifested in the range from 0.5 to 10 Hz and higher, i.e. in the range in which the existing passive and active vibration isolation systems do not work effectively: pneumatic, hydraulic, piezoelectric, etc. [1-8]. Solving the problem of effective protection against external vibration disturbances in the low-frequency region requires fundamentally new approaches based on the use of high-precision devices that provide active vibration isolation and positioning of the protected object in the submicron range with millisecond speed [9].

Magnetorheological (MR) elastomers are promising materials for use both in the atmosphere and in a vacuum as active elements of positioning and vibration-insulating mechanisms to improve the quality of research and technological processes [10]. At present, the vacuum characteristics of MR elastomers have been little studied, in particular, the processes of desorption and the partial composition of the released gases from the surface and from the volume of the material have not been
studied with regard to its complex spatial structure. A photograph of an MR elastomer obtained with a metallographic microscope with a magnification of 1600 is shown in Figure 2. In transparent silicone rubber, spherical particles of carbonyl iron 1...10 microns in size, structured under the action of a magnetic field in chains, are visible. MR elastomers belong to the class of so-called “smart materials” - “smart materials”, whose properties change under the influence of a magnetic field. MR elastomers are obtained by dispersing the magnetic powder in liquid silicone rubber, followed by polymerization of the composition in the form [11].

Carbonyl iron powder with spherical particle sizes from 1 to 10 microns is used as a magnetic filler. To improve compatibility with the silicone matrix, powders are modified with surfactants and organosilicon compounds.

Figure 1. Design of high vacuum scanning electron microscope. 

Figure 2. Photograph of MR elastomer based on carbonyl iron.

The results of experimental studies of the parameters of transients during the operation of a high-precision drive based on the MR elastomer with a closed control system, which is also an active damper (Figure 3) are presented. The amplitude and frequency characteristics of the damper and vibration-isolating platform with an open-loop control system in semi-active mode are shown based on four dampers and four elastic suspension nodes.

Figure 3. Active damper with sensor installed.
The purpose of the first series of experiments was to evaluate the quality parameters of transients of a closed control system of an active damper, depending on the transmission coefficient of the regulator. To control the active damper, a personal computer with a LabView program was used, a National Instruments USB-6009 ADC/DAC unit, an amplifier unit consisting of 4 amplifying modules based on operational amplifiers, a DL6220/ECL2 capacitive displacement sensor with a measurement error of 0.1 micron.

The active damper (Figure 3) is an electromagnetic drive with damping properties, containing an electromagnetic coil, magnetic core, and membrane based on an MR elastomer with a rigid center [10]. Creating a magnetic field in the membrane, you can adjust the elastic properties of the membrane of MR elastomer and move the hard center in the axial direction.

As a result of the experiments, graphs of transients were obtained for various values of the transfer coefficient \( k \) of the control system controller (Figure 4). From the presented graphs, it can be seen that with an increase in the transmission coefficient \( k \) of the regulator, the oscillation and the magnitude of the system overshoot increase while maintaining a practically unchanged time of the positioning transition.

![Figure 4. Transient graphs when moving the active damper with a closed control system of 200 micron for different values of the transfer coefficient \( k \) of the controller: 1 – 0.002; 2 – 0.005; 3 – 0.01.]

2. Research of the transfer coefficient of the amplitude of the active damper

The purpose of further research was to evaluate the effectiveness of the dampers in semi-active mode. It is known that the use of the MR effect allows you to adjust the stiffness coefficient of the elastic membrane made of MR elastomer by changing the magnitude of the magnetic induction and, accordingly, the frequency and accuracy characteristics of the active damper [11]. Due to this, it is possible to achieve a shift in the resonant frequency of the sample. This allows you to configure the device to work in the desired frequency range.

To carry out studies of the damper in semi-active mode on an experimental test bench, the scheme of which is shown in Figure 5, the following instruments were used: amplifier 1, personal computer 2, ADC 3, piezoelectric accelerometers 4 and 5, active damper 6, source of vibration disturbances 7 (Data Physics Vibrator V300), power supply unit 8 (Mastech). A feature of piezoelectric accelerometers 4 and 5 is the integrated integrator, which allows translating the obtained vibration acceleration values into vibration displacement values. In Figure 6 shows a general view of the experimental stand and its main elements: an active damper 1, a snap-in 2 for mounting the damper, a source of vibration disturbances 3.
The experimental procedure is as follows: from the power supply 8 to the damper 6 a fixed control current in the range of 0-1 A is supplied, a control program is activated on the personal computer 2 that activates the source of vibration disturbances 7. The measurement parameters are selected (frequency range 15-200 Hz, measurement time 2 min.). Accelerometer 4 measures the acceleration of a source of vibration disturbances. Accelerometer 5 measures the acceleration of the hard center of the active damper membrane 6. The signal from the sensor enters the ADC 3, after which it is stored in the control program on the personal computer 2.

As a result, experimental values of vibration displacement for the frequency range of 15–200 Hz for each active damper were obtained. Data processing was performed in Microsoft Excel. The resulting graphs of the transmission coefficient $K$ amplitude of vibration displacement versus frequency are presented in Figure 7.

The resulting graphical dependence can be divided into two sections. The first section of the resonance is 15-76 Hz, while the peak of the resonance is at a frequency of about 48 Hz, which corresponds to the natural frequency of the damper. An increase in the control current contributes to a decrease in the transmission coefficient $K$ from a value of 3.18 with a zero control action, to a value of 2.77 for a control current 1A and a shift of the resonance region to the left (the resonance region with a control current 1A 15-70 Hz).

The second section of effective vibration damping 77–200 Hz is characterized by a tendency for the transmission coefficient $K$ to decrease with an increase in the frequency of vibrations (minimum value $K = 0.29$ without control, minimum value $K = 0.28$ for a current of 1 A at a frequency of 200 Hz). Thus, the dampers in the semi-active mode of operation are most effective for the frequency range of 80-200 Hz, the natural frequency of the damper is 48 Hz.
Figure 7. Graph of the transfer coefficient of the amplitude of the vibration displacement of the damper on the frequency in a semi-active mode for the values of the control current: 1 – 0A; 2 – 0.5A; 3 – 1.0A.

3. Research of the amplitude transfer coefficient of the platform vibration displacement

The next stage of research is to evaluate the performance of the vibration-insulating platform in a semi-active mode for the frequency range 15-100 Hz. The resonant zone of the dampers is in the frequency range 15 ... 80 Hz, respectively, it is necessary to evaluate the effectiveness of the platform in this area.

To conduct a research platform in the semi-active mode on an experimental stand, the scheme of which is shown in Figure 8, the following instruments and devices were used: amplifier 1, personal computer 2, ADC 3, accelerometers 4 and 5, platform 6, power supplies 7 and 8; source of vibration disturbances 9. Anti-vibration platform 6 contains four active dampers and four elastic suspension assemblies.

The methodology of the experiment is as follows. A fixed control current from the power supply 7 and 8 is supplied to the electromagnetic coil of each damper. On personal computer 2, a control program is started, activating the operation of the source of vibration disturbances 9. Measurement parameters are selected (frequency range 15-100 Hz, measurement time 2 minutes). Accelerometer 4 measures the acceleration of the bottom plate of the platform. Accelerometer 5 measures the acceleration of the top plate of the platform. The signals from the sensors 4, 5 are received in the ADC 3, and then stored in the control program on a personal computer.

Figure 9 shows a general view of the experimental stand, containing platform 1, accelerometers 2 and 3, snap-in 4 for mounting the platform, vibrator 5, power supply units 6. As a result, experimental values of vibration movements for the frequency range 15-100 Hz were obtained. Data processing was performed in Microsoft Excel. The resulting graphs of the transmission coefficient K amplitude of the vibration displacement from the frequency are shown in Figure 10.
The resulting graphical dependence can be divided into two sections. The first section of the resonance 15-39 Hz contains two peaks at frequencies of 21 and 28 Hz. An increase in the control current contributes to a decrease in the transmission coefficient \( K \) at the first peak (from a value of 3.26 — with zero control action, to a value of 3.22 for a control current of 0.55A) and a shift of the resonance region to the left (resonance region at a control current of 0.55A 15-38 Hz).

The second section of effective vibration damping 40–100 Hz is characterized by a tendency for \( K \) to decrease with an increase in the frequency of vibrations (minimum value \( K = 0.18 \) without a control action, minimum value \( K = 0.16 \) for a current of 0.55 A at a frequency of 100 Hz). Thus, the platform in the semi-active mode of operation is most effective for the frequency range of 40-100 Hz, the natural frequencies of the platform are 21 and 28 Hz. Ensuring effective vibration isolation in the region of resonant frequencies can be achieved through the use of a closed-loop control system in the mode of stabilization of the platform, which is the subject of further research.

4. Research of the vacuum characteristics of MR elastomer
As noted earlier, MR elastomers are promising materials for use in a vacuum as active elements of positioning and vibration-insulating mechanisms. Let us consider a model of outgassing from the near-surface layer of an MR elastomer. In order to study the gases emitted, an experiment was conducted...
using an exhausting port with a vacuum chamber. For research, a sample of the elastomer was placed in a sealed copper tubulation. The evacuation of the vacuum system was carried out in two stages: fore vacuum pumping using a rotary vane pump and high vacuum pumping using a diffusion pump. The pumping process was observed on the screen of the control unit, and a computer connected to the quadrupole mass spectrometer was also connected to the control system.

To measure the partial pressures of gases that have the greatest impact on the total pressure in the pumped volume, at each time point the mass spectrometer analyzed the masses of gases in the range of 1-200 amu. Experiments were carried out on the outgassing of the MR elastomer during its subsequent processing: pumping the tubulation at room temperature to a limiting pressure of \( 5 \times 10^{-5} \) Torr; heating the tubulation to 150°C for 10 minutes, holding at this temperature for 20 minutes and then cooling. The data obtained from the mass spectrometer were used to plot pressure spectra for atomic mass units at each time interval. The graph at a warm-up temperature of 150°C is shown in Figure 11.

After analyzing the graphs obtained, the masses with the maximum pressure values (the largest peaks in the graphs) were identified, gases with these masses were identified. It was revealed that during the degassing of the MR elastomer, gases such as hydrogen, water, nitrogen, and carbon dioxide are released, and as the temperature rises, an additional gas peak appears on the mass of 72, presumably such mass may be isopentane \( C_5H_{12} \).

![Figure 11. Graf of gas pressure versus atomic weight at temperature 150°C.](image)

For each of the maximum masses, graphs of the dependence of the partial pressure on the pumping time are plotted. The resulting graph is shown in Figure 12. According to the schedule, we can talk about the intensity of pumping various gases. At room temperature, the partial pressures of hydrogen, carbon, and carbon dioxide are sufficiently small, while the release of water from the samples is large. When heated to 150°C from the graph (Figure 12), it can be seen that over time the partial pressure of nitrogen (pos. 2), hydrogen (pos. 3), isopentane (pos. 4) and carbon dioxide (pos. 5). The partial pressure of water (pos. 1) decreases with time, but a surge is visible. This change is possible because the thickness of the MR elastomer has warmed up and the flow of gases from it has begun, and the fact that the partial pressure of gases has begun to increase also indicates this. By the values of the masses of the maximum emitted gases, it can be seen that they are part of the atmospheric air; they are not specific to the pumped volume and MR elastomer. The graph shows that the maximum partial pressure has water vapors, this is due to the fact that all the components included in the MR elastomer have a water base, when pumping and heating water vapor diffuses to the surface and evaporates.
Figure 12. Change in the partial pressure of gases in time at the temperature 150℃ for atomic masses: 1 – 18 amu; 2 – 28 amu; 3 – 2 amu; 4 – 72 amu; 5 – 44 amu.

When heated, a specific gas appears - isopentane C₅H₁₂. The release of this gas is possible from the modifier (water-repellent agent NGL - 94), which is part of the MR elastomer. The partial pressure of this gas is two orders of magnitude lower than the limiting pressure of the vacuum system, thus we can say that this gas has a slight effect on the total pressure in the chamber.

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