579. Investigation of dynamic of smart valve using holographic PRISM system

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Abstract. The purpose of this work is to find dynamic characteristics of a new smart valve with piezoactuator used in different mechatronic systems, in medicine, alimentary industry, etc. Novelty of this valve is that one of the parts of its control device, i.e. membrane, is comprised of two raster steel disks (each disc has the same number of notches) and the flow is controlled by means of optical interference effect generated between them. With the help of holographic PRISM system we investigated which piezocylinder, segmented or nonsegmented, is better to use in the system of smart valve. Also we represented the original patented scheme of the smart valve.

Keywords: valve, smart materials, piezoceramic actuator, holographic method.

Introduction

The environment and technological inventions have had a big influence on the recent revolution in electronics, computer, management and chemistry engineering. Now we can speak not only about classical mechanics, but about „smart" materials, adaptive mechanisms, nanotechnologies too. The new mechanisms that have very small dimensions can work very fast, safely and reliably by using less energy than the former ones.

Valves of small dimensions [1] with piezoceramic actuators [2, 3] are used more and more often. Their examples can be found in scientific and engineering literature. Our purpose was to create a new valve which function is based on the interaction of two raster discs. A piezoceramic cylinder is used for making a rotational move of one of the discs. In the article, the nonsegmented and segmented piezocylinders were analyzed and it was established which one is more purposive for using in the system. The amplitude of the raster disc vibrations was established by using modern PRISM systems optical setup.

The valve that was analyzed in this article consists of the case where the control mechanism with a piezoceramic actuator is fixed. The control mechanism (membrane) consists of two raster steel discs, one of them is directly tightly glued to the piezocylinder, the other one is fixed in the fastening ring. During the experiment, the amplitude of the glued raster disc vibrations was determined, when the disc is glued to the nonsegmented and segmented piezocylinder. The number of raster cuts in the both discs equals n, therefore we can control the leaking flow from totally closing to fully opening it. The disc fixed in the ring has a possibility to rotate with respect to the first glued disc and control the leaking flow. Our purpose was to establish which of the actuators is more purposive to use - nonsegmented or segmented piezocylinder - to obtain a bigger rotating moment. The piezocylinder is connected with the control block and a generator.

The novelty of this valve is characterized by the fact that control mechanism, i.e., the membrane is made of two raster steel discs, an optical interference effect is obtained between them. With the help of this effect the flow of liquid or gas leaking is controlled. By using the piezoceramical actuator made of „smart“ materials, we can also rotate one of the raster discs very fast and control the flow to leak through the membrane very fast at the same time. It is known that a bigger vibration amplitude creates a better rotating moment that influences quick action. Therefore we established vibration amplitudes of the nonsegmented and segmented piezocylinder by using the holographic PRISM system to choose the best valve control modes. This research helps to establish the best valve control strategy.

Construction and working principle of the smart valve

New patented smart valve is shown in figure 1.

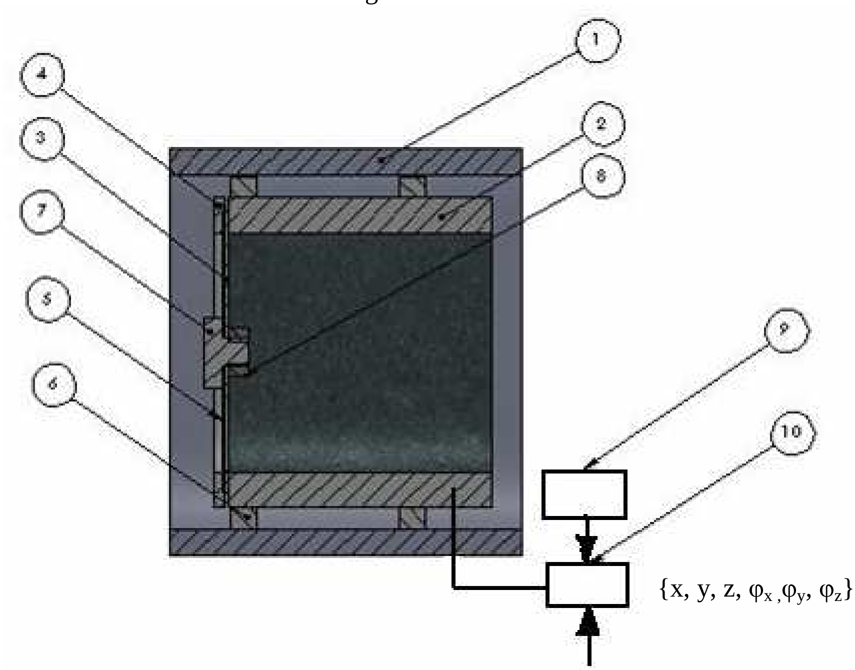


Fig. 1. The valve consists of: 1- body; 2- piezoceramic cylinder; 3 and 5- raster discs; 4-metal ring; 6- rubber fastening rings; 7- bolt; 8- nut; 9- generator; 10- control block.

The valve functions in the following way: the piezoceramic cylinder 2 is fixed in the body 1 on two rubber fastening rings 6 (in this system are two rubber rings). The rings 6 perform a sealing function and they do not allow liquid or air to leak over the edges. The raster disc 3 is glued to the piezoceramic cylinder 2. The raster disc 5 is glued in the ring 4. Bolt 7 together with the nut 8 perform function of the raster discs centering and mounting. The piezoceramic cylinder 2 is connected with the control block 10 and generator 9.

The principle of operation can be explained as follows. Traveling deformation waves are generated in the piezoceramic cylinder 2 when the control block 10 and generator 9 is connected to it. Glued raster disc 3 to piezoceramic cylinder 2 start to vibrating. Amplitude of the raster disc 3 vibrations generates the rotation moment and the metal ring 4 with the glued raster disc 5 start to rotate. As the both raster discs 3 and 5 have the same number of raster cuts, we can get full closure or opening depending on the angle of raster disc 5 rotation α. We can also rotate so that leaking is not maximal or minimal.

Experimental setup

A number of experimental studies are needed in order to ensure high dynamic accuracy of operation of the optical scanners. In most cases the exciting frequencies are quite high, and the amplitudes corresponding to them are measured in micrometers. Therefore the holographic method can be effectively applied for the visual representation of dynamic processes taking place in the waveguide of the optical scanner. The most effective method for studying the dynamic processes is the method of digital holographic interferometry [4-6].

PRISM system combines all the necessary equipment for deformation and vibration measurement of most materials in a small lightweight system. A standard system includes holography and computer systems integrated with proprietary state-of-the-art software. The main parts of the PRISM system setup are presented in Fig. 2 [7].

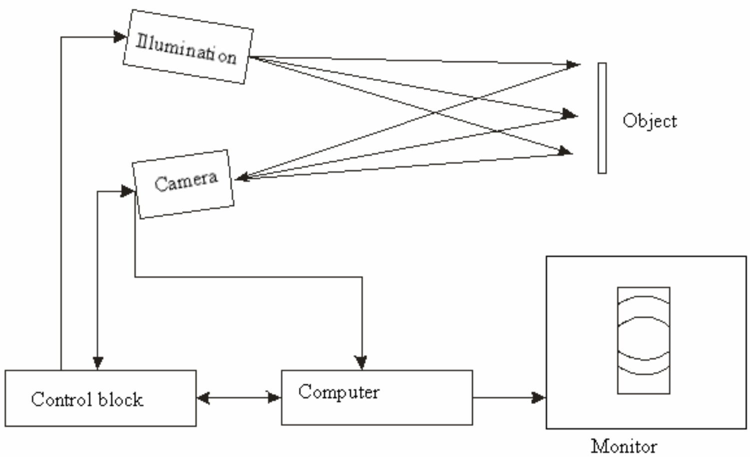
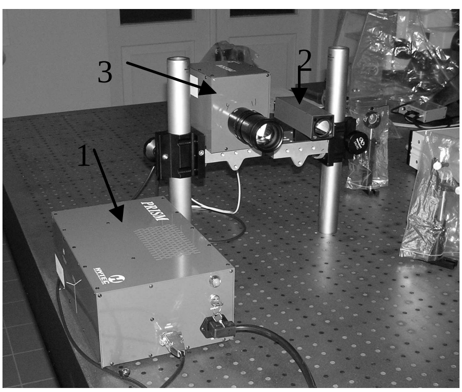


Fig. 2. PRISM system optical setup



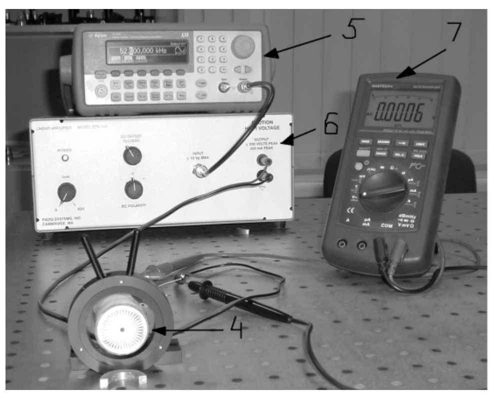


Fig. 3. PRISM system: 1 - control block, 2 - illumination head of the object, 3 - video head, 4 - piezoceramic cylinder with raster disk, 5 - amplifier, 6 - generator, 7 - tester

The PRISM system shown in Figures 2 and 3 is a two beam speckle pattern interferometer. The laser beam directed at the object is the object beam, the other beam, which goes directly to the camera, is the reference beam. Laser light is scattered from the object and collected by the camera lens, which also images the object onto the CCD camera sensors. Shape changes that occur during the process produce fringes on top of the image of the object (Fig. 4), which is displayed on the monitor.

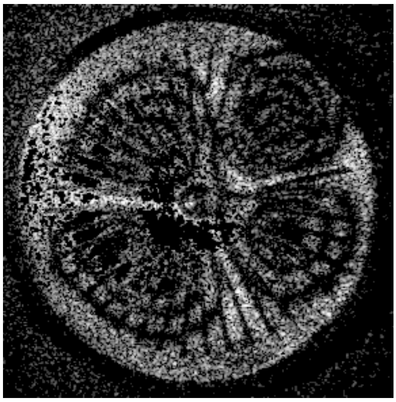


Fig. 4. Time-average hologram of the raster disc excited with segmented cylindrical piezoceramic actuator (133.6 V, 12.9 kHz)

Mathematical description of time-average holography

It is necessary to make assumption that time varying displacement is along z-axis, which, in the holographic arrangement used, is along the line of sight between object and observer. The displacement is a periodic function of time and the development is simplified if the displacement is allowed to vary only with x and time, it is presumed that $Z(x)\sin(\omega t)$. If $\phi(x,y)$ is the resting phase distribution, then the object complex amplitude at the film plane is:

$$U_O = A(x,y)e^{i\left[\phi(x,y)+\frac{4\pi}{\lambda}Z(x)\sin\omega t\right]}; \tag{1}$$

where λ is the wavelength of the laser.

The time-average hologram is recorded with object beam and reference beam for a time T that is longer than several periods of the vibration. The reconstructed object wave has complex amplitude that is proportional to the time average of the U_O over time T, which is:

$$U_{O\ av} = A_{av}(x,y)\frac{1}{T}\int_0^T e^{i\left[\phi(x,y)+\frac{4\pi}{\lambda}Z(x)\sin\omega t\right]}dt = J_0\left[\left(\frac{4\pi}{\lambda}\right)Z(x)\right]. \tag{2}$$

The J_0 is the zero-order Bessel function. The irradiance is calculated as:

$$I(x,y) = A^2(x,y)J_0^2\left[\left(\frac{4\pi}{\lambda}\right)Z(x)\right]. \tag{3}$$

In this case, the image has superimposed on it a system of fringes that correspond to the minima of the square of the zero-order Bessel function [8].

The following procedure should be completed in order to calculate the amplitude of vibrations of the plate shape object, which is mounted tightly by its end in the fixture. The fringes of the vibrating plate, obtained by the time-average holographic interferometry are schematically shown in the Figure 5. The point *P* is in the middle of the second dark fringe. The centres of the dark fringes coincide with the points of the plate, where the amplitude of vibrations *Z(x)* is such, that the Bessel function obtains zero value.

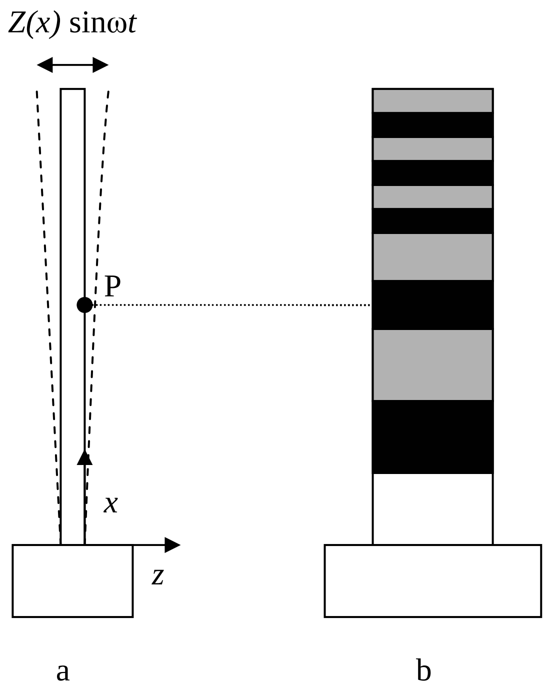


Fig. 5. Vibrating plate: a – the view from the side; b – the view from the front [8]

The higher-order (higher then 20) zeros of the Bessel function (ξ_n) are set almost equally and can be depicted by the following equation [8]:

$$\xi_n = (n - \frac{1}{4})\pi + \frac{1}{8}\left[\left(n - \frac{1}{4}\right)\pi\right]^{-1} \quad (4)$$

Then amplitude of the vibrations (Z) in the point P can be determined by the following equation:

$$\xi_n = \frac{4\pi}{\lambda} Z(P). \quad (5)$$

Measurement error

For all kinds of experiments it is important to determine the measurement error. For example maximum measured vibration amplitude of the raster disc is 1563 nm. This amplitude was determined for the raster disc excited with voltage of 62 V at 4.2 kHz frequency. This amplitude was determined according to the image printed on paper. Printed raster disc had 70 mm diameter. Distances among fringes were measured using a ruler. If amplitude (*A*) is distributed evenly through all diameter (*D*) of the raster disc and fringes position measurement error is 0.5 mm (Δ), then maximum absolute error (*AE*) of measurement could be calculated according to the formula:

$$AE = \frac{A}{D} \cdot \Delta . \tag{6}$$

$$AE = \frac{1563nm}{70mm} \cdot 0.5mm = 11.2nm . \tag{7}$$

Then absolute error of measurements is 11.2 nm. Absolute error (*AE*) divided by measured amplitude (*A*) and multiplied by 100% is relative error (*RE*):

$$RE = \frac{AE}{A} \cdot 100\% . \tag{8}$$

Substituting formula (5) to formula (7) gives that relative error that depends only on the diameter of the raster disc and the accuracy of position measurement. Furthermore, relative error does not depend on the measured amplitude.

$$RE = \frac{\frac{A}{D} \cdot \Delta}{A} \cdot 100\% = \frac{\Delta}{D} \cdot 100\% \tag{9}$$

$$RE = \frac{0.5}{70} \cdot 100\% = 0.7\% \tag{10}$$

Then the determined relative error is equal to 0.7%. This result demonstrates that vibration measurement of the membrane using PRISM system is sufficiently accurate.

Experimental results

Dynamic properties of the raster disc excited using nonsegmented and segmented cylindrical piezoelectric actuators (Fig. 6) were analyzed at different voltages and frequencies.

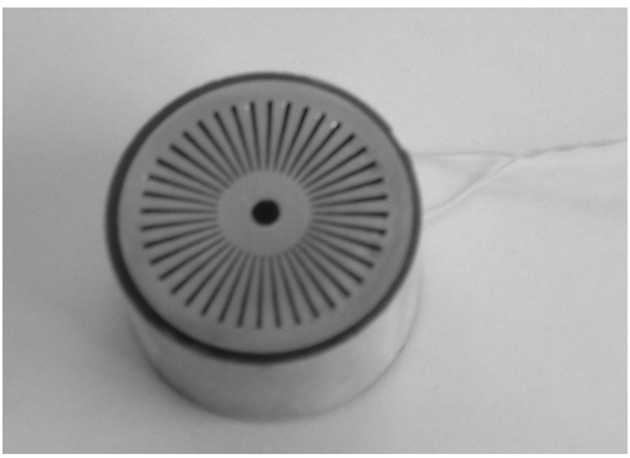


Fig. 6. Piezoelectric actuator with glued raster disc

Time average holograms of the raster disc excited with nonsegmented cylindrical piezoelectric actuator (frequency 4.2 kHz, voltage: 10 V, 15 V, 20 V, 40 V, and 62 V) are presented in Figure 7. Amplitude of vibrating membrane dependence on voltage of excitation signal is presented in Figure 8. From the graph it is clear that vibration amplitude dependence according to excitation voltage is linear (Fig. 8). It means that operation of the raster disc could be easily controlled using linear voltage controllers.

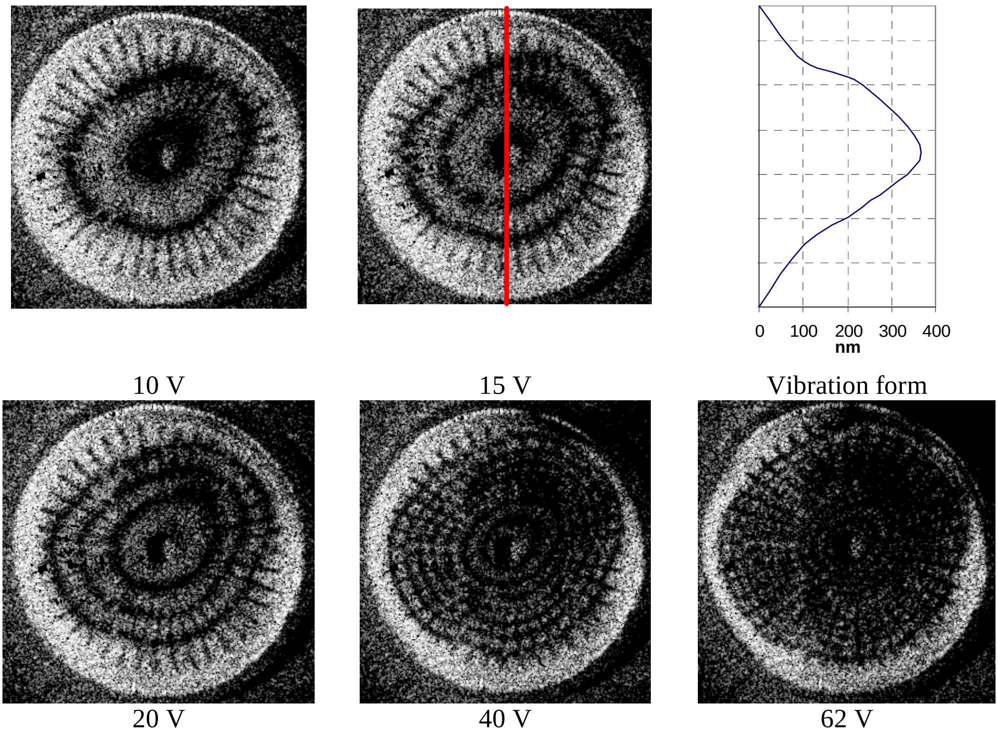


Fig. 7. Time average holograms of the raster disc excited with nonsegmented cylindrical piezoelectric actuator (4.2 kHz)

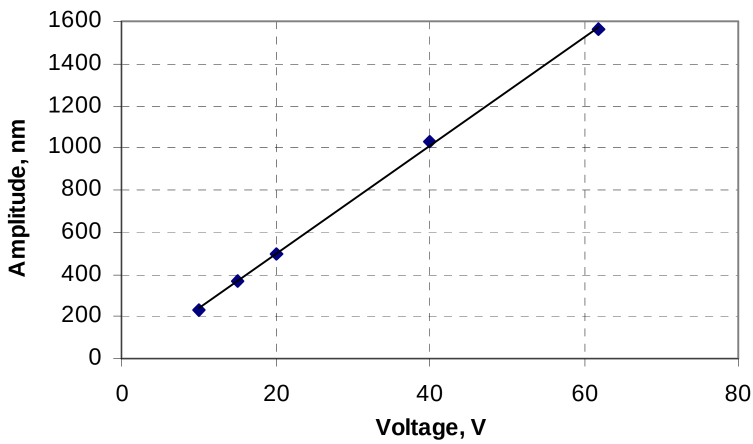
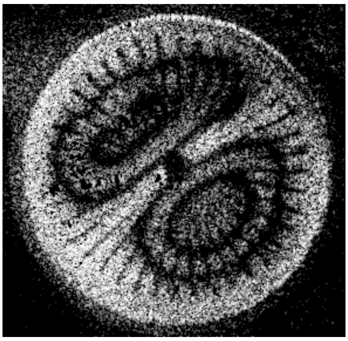
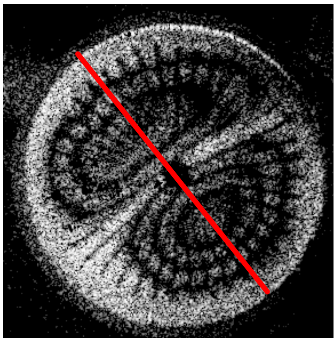


Fig. 8. Amplitude of vibrating membrane dependence on voltage of exciting signal

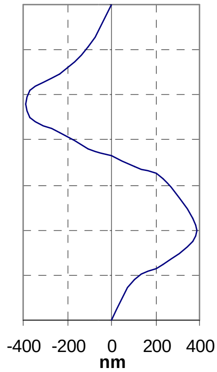
Time-average holograms of the raster disc excited with nonsegmented cylindrical piezoelectric actuator at 9.7 kHz frequency is presented in Figure 9. In such conditions vibration form had two peaks of 400 nm at 65.4 V. Higher excitation frequency produces higher order vibration forms. It enables us to change operational speed and mode.



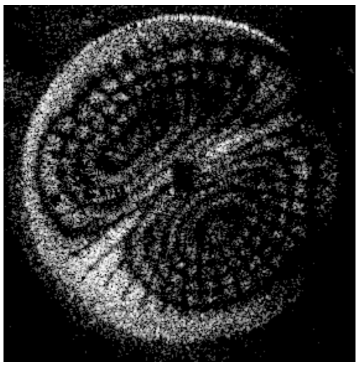
43.7 V (300 nm)



65.4 V

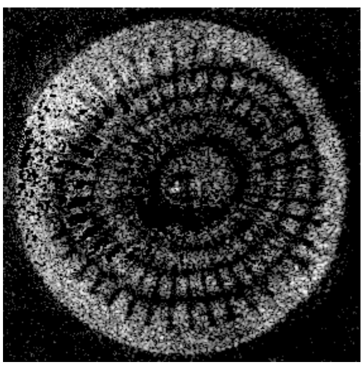


Vibration form



109 V (565 nm)

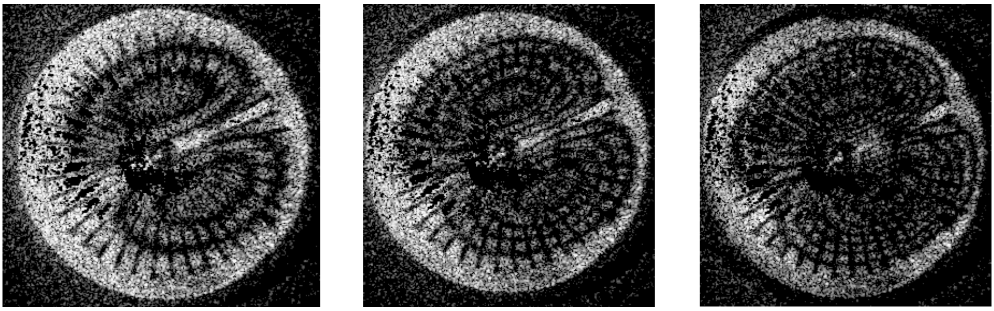
Fig. 9. Time-average holograms of the raster disc excited with nonsegmented cylindrical piezoelectric actuator (9.7 kHz)



121 V (565 nm)

Fig. 10. Time average hologram of the raster disc excited with segmented cylindrical piezoelectric actuator (4.3 kHz)

Vibration form of the raster disc excited with nonsegmented and segmented cylindrical piezoelectric actuators was determined identical at the same frequency: Fig. 7 and Fig. 10 at the frequency of 4.2 kHz, and Fig. 9 and Fig. 11 at the frequency of 9.7 kHz.



36.1 V (300 nm) 78.6 V (565 nm) 125.1 V (831 nm)

Fig. 11. Time average holograms of the raster disc excited with segmented cylindrical piezoelectric actuator (9.7 kHz)

However raster disc excited with segmented cylindrical piezoelectric actuator produces higher vibration amplitude (Fig. 12) than excited with nonsegmented actuator at the same excitation frequency (9.7 kHz). It means that segmented piezoelectric actuator produces better rotating moment and it is more effective in real systems.

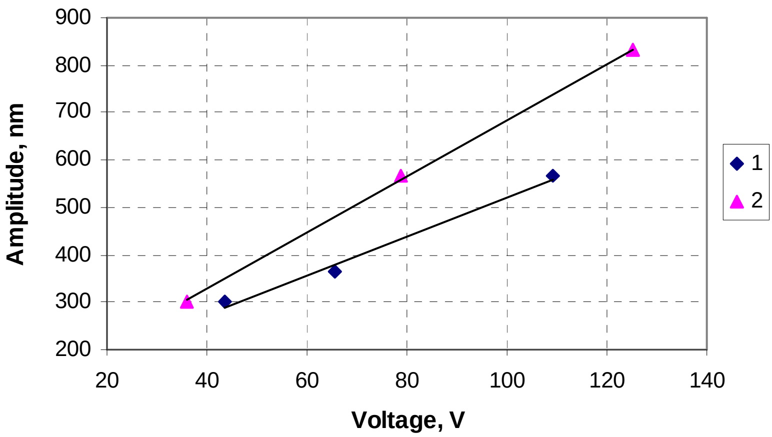


Fig. 12. Amplitude of vibrating membrane dependence on voltage of excitation signal for two types of actuators: (1) nonsegmented and (2) segmented piezoelectric actuators

Conclusions

Amplitude of the vibrating raster disc dependence on the excitation voltage is linear, so operation of the raster disc could be easily controlled using linear voltage controllers.

Segmented piezoelectric actuator produces better rotating moment and it is more effective in real systems, because raster disc excited with segmented cylindrical piezoelectric actuator produces higher vibration amplitude than excited with nonsegmented actuator at the same excitation frequency.

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