

KAUNAS UNIVERSITY OF TECHNOLOGY

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**RESEARCH AND DEVELOPMENT OF
MANIPULATOR DRIVE WITH
ELECTORHEOLOGICAL FLUID**

Summary of Doctoral Dissertation

Technology Sciences, Mechanical Engineering (09T)

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The dissertation is available at the library of Kaunas University of Technology.

KAUNO TECHNOLOGIJOS UNIVERSITETAS

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**MANIPULATORIAUS PAVAROS SU
ELEKTROREOLOGINIŲ SKYSČIŲ
KŪRIMAS IR TYRIMAS**

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INTRODUCTION

Implementation of electrorheological fluid in array and planar manipulators drive is investigated in this work. Electrorheological fluid (ERF) has been chosen as active material which has property to change its viscosity under influence of electrical field. ERF itself, its fundamental properties and working modes are described at the beginning of this work. Research and development of using ERF as actuator in design of manipulators drive is described further. Possible control methods and dynamic models together with experimental research of array and planar manipulator systems are considered here as well. Certain mechanisms – array and 2-link planar manipulator are considered as objects of research of this work.

The research object of this work is to investigate implementation of ERF in manipulators drive systems and independent actuation of manipulator elements by one actuator – electrorheological fluid. In order to achieve these goals the following issues has to be considered in this work: theoretical and experimental investigation on ERF working modes in array and planar manipulators drives; development of principal design schemes of manipulator drive based on ERF; design and analysis of dynamic models of array and planar manipulators drives; research on advantages and disadvantages of using controllable fluids in thin layers of electrodes of manipulator drives.

Research methods

Theoretical, analytical and experimental work was cared out during this research. Analytical models were investigated. Results were processed and presented using mathematical computing software. Originally designed equipment was used in experimental research. Piezoelectric active materials, *Hewlett - Packard* and *National Instruments* hardware were used for the generation of vibrations, measurements and analysis of the manipulator drive parameters. Originally composed data acquisition software, based on the *National Instruments* programming package *Labview* was used for recording and analysis of measurements data. Prototypes of planar and array manipulators drives were designed using the results of the research.

Scientific novelty

1. Method of transportation of solid object by electrorheological fluid is introduced in this work. Dynamic model which describes this transportation is created. Main parameters from which shear stress of ERF depends in manipulator drives are determined theoretically and experimentally.

2. Variable structure underactuated manipulator is proposed. Functionality of such manipulator is investigated under conditions of control by angular acceleration of output link.
3. Original multilayer valve actuated by electrorheological fluid is developed. Relation between geometrical properties of valve and electrorheological effect is determined.
4. Control method of manipulator drive such as multiplexing of voltage and pressure is proposed here. This method allows avoiding separate connection of control signal to each of the manipulator elements. This method is created and tested by "Smart Technology ltd" (UK).
5. Advantages and disadvantages of using ERF in thin layers are considered in this work. The new method of avoiding some disadvantages is proposed here using piezoelectric actuators.

Publications and approbation of the work

Author of this dissertation presented fourteen scientific works in Lithuanian and international publications, as well as two articles in the journal "Mechanika" which corresponds to the requirements of the Lithuanian Council of Science. Author participated and presented his research in thirteen scientific - technical conferences and seminars in Lithuania and abroad.

New construction of an array manipulator drive has been proposed and request to obtain patent of Lithuanian Republic has been submitted.

Scientific work has been carried at Kaunas University of Technology under European Union FRAMEWORK V Project: IST-2001-32240 *ITACTI*, "*Smart Interactive Tactile Interface Affecting Graphical Display for The Visually Impaired*". Project's coordinator is Prof. Jeffrey A.G. Knight from De Montfort University.

Presented for the defense

1. Results of theoretical and experimental research of ERF working modes in manipulator drive.
2. Prototypes and principal schemes of 2-link underactuated and array manipulators that work in shear mode.
3. Examples of practical use and analysis of disadvantages using ERF in thin layers and method proposed to avoid such disadvantages.
4. Results of theoretical and experimental research of ERF behavior in thin layers and method proposed to solve clogging problem that occur in this case.

Structure and volume of the dissertation

Dissertation consists of an introduction, 5 chapters, and conclusions, list of author's publications and list of references. Total volume of dissertation is 104 pages, 76 figures and 14 tables.

1 ARRAY MANIPULATORS IN MANUFACTURING SYSTEMS

The adaptive (smart) materials contribute a lot now to the actuators' development and may be successfully used in array manipulators. The paper presents the research on the design and control of the array manipulator actuated by electrorheological fluid (ERF) that has the fundamental property to become solid-state under electric field action. This phenomenon allows controlling the stiffness and damping of the structure, which can be changed dynamically by applying high voltage.

When each actuator of the array manipulator has its own drive, production of such device becomes more complex and reliability or even durability is the problem that arises in that case. Possible solution of such problem can be original manipulator where all actuators (pins) are controlled by one drive – electrorheological fluid. A distributed manipulation system (Array manipulator) consists of a large number of identical actuators arranged in a planar array, combined with a control system creating and controlling movement of an object or simultaneous manipulations on a number of objects placed on the array. Line or 2-D Braille devices, in which manipulation is performed on a great number of pins ($m \times n$ matrix), can be attributed to the Array Manipulator class. The equation, which describes movement of main manipulator element – pin, is derived and the motion of manipulator pin is described. Some results are presented from Simulink model in order to show the influence of main factors to the movement of a pin.

This paper concludes with some review of future works for development. Some areas of future research include some key elements of mechatronics – optimization of manipulator construction and development of pin control algorithm, modeling and simulation.

2 MANIPULATOR DRIVE ACTUATED BY ELECTRO-RHEOLOGICAL FLUID

Electrorheological fluids are dispersions of small (up to 50 μm) dielectrical particles in fluids which have dielectrical properties: oils, etc. Viscosity of such fluids can be rapidly changed by applying electrical field (Fig. 1). Viscosity is proportional to strength of applied electrical field. Usual ERF changes its viscosity in milliseconds. This process is reversible: when electrical field is removed ERF returns to its initial state.

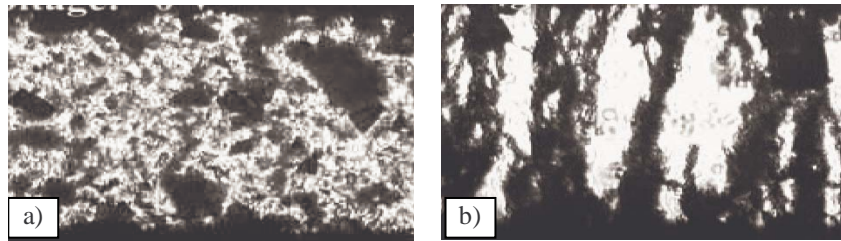


Fig. 1. ERF: a) not actuated; b) under actuation

There are used 3 ERF modes mainly. It is shear, squeeze and valve modes. In the first case surfaces of electrodes moves parallel each other. Therefore force of certain magnitude can be transferred between electrodes. Magnitude of generated force depends on area of electrodes and strength of applied electric field. In squeeze mode electrodes moves towards and backwards each other. Generated force also depends on the same parameters as in previous case, but under different law. Most interesting is valve mode. In this mode electrodes doesn't move at all but ERF does. It moves between electrodes. In this case we have electrically controlled valve where actuator is the same medium which has to be controlled. Valve mode has most potential practical implementation in active hydraulic systems such as dampers, artificial muscles, etc.

Manipulator Drive Actuated in Shear Mode

The dynamic model of an array manipulator drive is presented in Fig. 2. The pin of the manipulator (mass m), the actuating plate and ERF are shown schematically. The magnitude of the force transferred to the pin depends on the area of active surface of the pin and on the strength of electric field, and gap width, and also on the properties of ERF.

Let the origin of the coordinate system be located at the surface of the pin. Coordinate x is limited by the size of the gap (boundary conditions when $x = 0$ and $x = \Delta$) and there are no constraints along coordinate y .

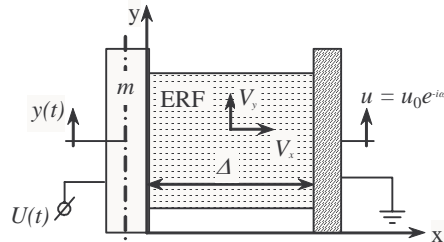


Fig. 2. The dynamic model of array manipulator drive

Let the actuating plate of the manipulator move under the law

$$u = u_0 e^{-i\omega t} \quad (1)$$

where u is the velocity and u_0, ω are its amplitude and frequency.

ERF is a fluid, but under the influence of a sufficiently strong electric field its viscosity becomes sufficient to actuate the movement of the pin if the gap between the electrodes is small. The dynamic analysis of such a system (see Fig. 2) is presented below.

ERF layer velocity at $x = \Delta$ must meet boundary conditions

$$v_x = v_z = 0, \quad v_y = u \quad (2)$$

With reference to the continuity condition, $div \vec{v} = 0$, and herewith $\frac{\partial v_x}{\partial x} = 0$, and

boundary conditions (2) considered, we have $v_x = 0$.

Therefore $v_y = 0$ and ERF motion equation is

$$\frac{\partial v}{\partial t} = \frac{\eta}{\rho} \frac{\partial^2 v}{\partial x^2} \quad (3)$$

where v, η, ρ are velocity, viscosity and density of ER fluid respectively. Solution of equation (3) is of such form

$$v = (A \sin kx + B \cos kx) e^{-i\omega t} \quad (4)$$

Considering boundary conditions

$$x = 0, \quad v = w \quad \text{and} \quad x = \Delta, \quad v = u \quad (5)$$

where w – velocity of the pin,

we shall get the solution of equation (3)

$$v = \left(\frac{u_0 - w_0 \cos k\Delta}{\sin k\Delta} \sin kx + w_0 \cos kx \right) e^{-i\omega t} \quad (6)$$

where w_0 is pin velocity amplitude and k wave number.

The properties of ERF when electric field is applied to it are outlined by Bingham pattern

$$\sigma = \alpha E^2 + \eta \frac{\partial v}{\partial x} \quad (7)$$

where σ is stress of ERF, α - constant, E - electric field strength. Force pulse transferred to ERF is

$$S = \frac{\alpha}{\Delta} \int_{t_0}^{t_p} (E^2(t)) dt \quad (8)$$

Pin movement in ERF considering actuation by electric field is described by the equation

$$m \frac{dw}{dt} = -mg - Q\eta k \left[w \text{ctg} k \Delta - \frac{u}{\sin k \Delta} \right] + V \frac{\alpha}{\Delta} \omega \int_{t_0}^{t_p} E^2(t) dt \text{sgn}(u - w) \quad (9)$$

where Q is surface area of the pin dipped into the fluid; $[t_0, t_p]$ time interval of electric field action; $E(t)$ – the law of electric field strength variation; V active volume of ERF being between plate and pin.

Let the ERF is affected by rectangular pulse. Recording it by Fourier series we have

$$E(t) = \frac{a_0}{2} \sum_{n=1}^{\infty} (a_n \cos n\omega t + b_n \sin n\omega t) = \frac{a_0}{2} + \sum_{n=1}^{\infty} A_n \cos(n\omega t - \psi_n) \quad (10)$$

where $A_n = \sqrt{(a_n^2 + b_n^2)}$ and $\psi_n = \arctg \frac{b_n}{a_n}$.

Assume, that amplitude of pulse is E_0 and pulse time - τ . Then

$$\begin{aligned}
E_0 &= \frac{a_0}{2} = \frac{1}{\tau_0} \int_0^{\tau} E(t) dt = \frac{1}{\tau_0} \int_0^{\tau} E dt = E_0; \\
a_n &= \frac{2}{\tau_0} \int_0^{\tau} E \cos nwt dt = \frac{E}{n\pi} \sin nw\tau; \\
b_n &= \frac{2}{\tau_0} \int_0^{\tau} E \sin nwt dt = \frac{E}{n\pi} (1 - \cos nw\tau); \\
A_n &= \frac{2E}{n\pi} \sin \frac{nw\tau}{2}; \psi_n = \text{arctg} \frac{1 - \cos nw\tau}{\sin nw\tau} = \frac{nw\tau}{2}
\end{aligned} \tag{11}$$

where $w = n \frac{2\pi}{\tau}$.
Thus we have

$$E(t) = E_0 \left[1 + \frac{2}{\pi} \sum_{n=1}^{\infty} \frac{\sin \frac{nw\tau}{2}}{n} \cos \left[nw \left(t - \frac{\tau}{2} \right) \right] \right] \tag{12}$$

The equation, which outlines the movement of the pin, is

$$m \frac{dw}{dt} = -mg - kQ\eta \left[wctgk\Delta - \frac{u}{\sin k\Delta} \right] + \frac{2\pi\alpha}{\Delta\tau} V \left[E_0^2 + \frac{1}{2} \sum_{n=1}^{\infty} A_n^2 \right] \text{sgn}(u - w) \tag{13}$$

when t varies in the interval $[t_0, t_p]$,
and

$$m \frac{dw}{dt} = -mg - Q\eta k \left[wctgk\Delta - \frac{u}{\sin k\Delta} \right] \tag{14}$$

when t varies outside the interval $[t_0, t_p]$.

Simulation of the Pin Motion

A Simulink model was created on the base of equation (13) derived in the analysis of the dynamic model shown in Fig. 2.

The investigation shows that the pin moves even without an applied electric field due to the viscosity of ERF. This situation is illustrated by Fig. 3. The

short pulse of the voltage applied to the electrodes causes the pin to move and change its oscillation position.

The magnitude of the generated force depends on the parameters of the system and is described by the last member on the right side of equation (13). Mainly it depends on the strength of the electric field between the electrodes, which can be changed by the gap size or voltage amplitude.

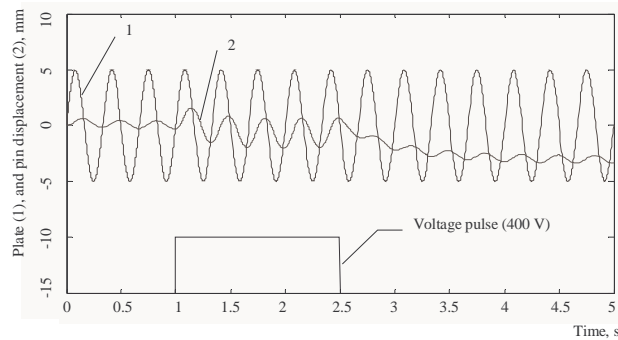


Fig. 3. Diagram of the pin and plate displacement under longer actuation

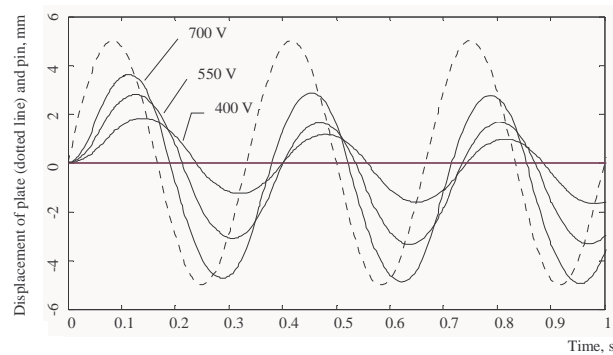


Fig. 4. Displacement tracking by the plate and the pin under different voltage strength

When voltage is applied to the pin for some period, it moves during it under the similar law as the plate does (Fig. 3) with some phase shift and the pin displacement depends on the magnitude of the generated force.

The system response to the constant voltage of 400, 550 and 700 Volts is shown in Fig. 4. It can be seen that the phase difference between the plate and pin movement is smaller when the magnitude of voltage is larger. The

magnitude of the pin oscillations becomes larger when voltage increases as well.

Squeeze Mode of ERF

To solve equations of motion J.L. Sproston used theory of surface lubrication and wrote equation which describes force p which is transferred to non-movable electrode:

$$p(t) = \frac{2\pi\tau_y a^3}{\Delta_0 - \Delta(t)} \left\{ \frac{1}{108} \left(\frac{\gamma}{X} \right)^3 + \frac{1}{X^3} \int_{\frac{\gamma}{3}}^X GS^2 dS \right\} \quad (15)$$

where a – radius of electrode, $\Delta_0 - \Delta(t)$ – actual gap between electrodes. γ - dimensionless constant, which Sproston determined equal to 10^{-4} .

Dimensionless magnitude S depends on radius r and is described by equation:

$$S(r) = \frac{d\Delta \cdot \eta}{dt(\Delta_0 - \Delta(t))^2 \cdot \tau_y} r \quad (16)$$

$X \equiv S(a)$ - S value on the edges of electrode. G is also dimensionless value of pressure gradient, described by equation:

$$G = -\frac{\Delta_0 - \Delta(t)}{2\tau_y} \frac{dp}{dr} \quad (17)$$

G can be precisely described by S and γ values by solving below presented cubic equation:

$$2G^3 - 3[2S + (1 - \gamma)]G^2 + 1 = 0 \quad (18)$$

It is possible to get instant values of force p solving 15 – 18 equations using digital methods.

During investigation it was observed that this ERF mode is not so investigated as other modes. Calculations made by Sproston show that squeeze mode is less effective than shear or valve modes. This was confirmed by experimental research of this work. Regardless of this conclusion design of manipulator drive

actuated in squeeze mode could be compact and simple-operated. Common technologies of metallisation of polymers can be used in this case.

Manipulator drive actuated by ERF in single valve mode

In this case design of manipulator drive is similar as drive actuated in shear mode. The difference is that both electrodes are non-movable (Fig. 5.). Direction of electrical field lines is from one electrode to another – exactly as in shear mode.

Principle scheme is shown in figure 5. Such drive consists of: dielectrical pin 1, plate 2, housing 3, membrane 4, pin-electrode 5, cylindrical electrode 6. Volume 7 is filled with ERF through hole 8. ERF can easily fill gap between electrodes 5 and 6.

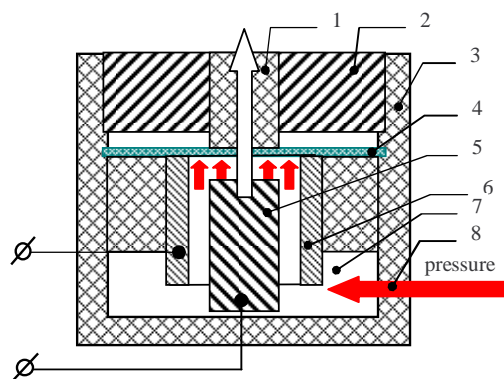


Fig. 5. Drive actuated in single valve mode

When volume 7 is pressurized with pressure p_1 , and if there is no voltage between electrodes, ERF deforms membrane 4. Membrane can move the pin 1 attached to it. When high voltage is applied to electrodes, ERF solidifies between electrodes and valve is closed. Thus it is possible to lock dielectric pin in any position.

Manipulator drive actuated by ERF in multilayer valve mode

The design of multi-layer valve is simple and similar technology that is developed in electronic industry can be used. In this case such valve consists of several layers of electrical conductor, separated by insulator. Number of layers and geometry of the valve depends on desired effect. The functional diagram of such valve is presented in Figure 6. It consists of number of thin layers of conductor (hatched in Fig. 6 a) and insulator between them (Fig. 6 b). Every

second layer of electrodes is connected to positive pole and rest layers are connected to negative pole. Working principle is based on effect when particles of ERF are connected in chains under strong electric field (Fig. 6 c).

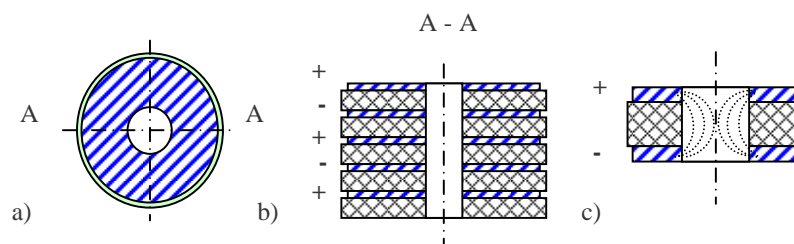


Fig. 6. Schematic Layout of Multi-Layer Valve

Two multi-layer valves of different geometry were tested in Kaunas University of Technology. In both cases test valves consists of 10 layers of electrodes. Parameters of first valve: diameter of hole 0.5 mm, thickness of insulator 0.5 mm. Second valve: diameter of a hole 0.5 mm, thickness of insulator 0.25 mm. In both cases electrodes were connected to DC voltage and air pressure was applied to ERF in a holes. Power consumption was measured at the same time under different voltage strength.

It was observed that effect is stronger in case of first valve 0,5 (hole) x 0,5 (insulator). Effect is stronger if we have more layers of electrodes (test was made with 10 layers). The ratio between holes' diameter and thickness of the insulator layer is a crucial factor and at least it should be less than 1. If it is more than 1, the effectiveness of the valve is reduced dramatically.

It is possible to control flow of ERF in case if there is difference of pressure before and after valve.

Control method of array manipulator

In this chapter method of control of array manipulator drive is described. Control method is based on voltage and pressure multiplexing. Example of 3x3 array to be controlled is shown in Fig. 7. Control of movement of pins filled with black (Fig. 7) is described below.

Known condition: all array elements are locked if all the rows are connected to -400V and all the columns are connected to +400V (voltage difference 800V) or to 0V (voltage difference 400V).

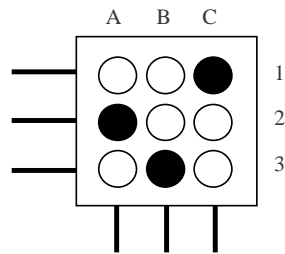


Fig. 7. Layout of array that consists of 3 x 3 elements

Action sequence:

1. All the elements have to be locked
2. System is pressurized
3. Voltages applied to separate elements of manipulator:
 - a. Row 1 = 0V; Column A = + 400V
 - b. Row 2 = - 400V; Column B = + 400V
 - c. Row 3 = - 400V; Column C = 0V.

Thus array element C1 is locked in upper position (system is still pressurized). All the rest elements are locked in initial position

4. Voltage is applied this way:
 - a. Row 1 = - 400V; Column A = 0V
 - b. Row 2 = 0V; Column B = + 400V
 - c. Row 3 = - 400V; Column C = + 400V

Thus array element A2 is locked in upper position (system is still pressurized). All the rest elements are locked in initial position.

5. Voltage:
 - a. Row 1 = - 400V; Column A = + 400V
 - b. Row 2 = - 400V; Column B = 0V
 - c. Row 3 = 0V; Column C = + 400V
6. Then all the elements are locked again.
7. Pressure is off.

Therefore all black elements are in place. The point of this control method is that all electrodes are locked in the beginning. Later elements of array are moved row by row. Row that needs to be moved gets 0V (the rest rows have 400V). Certain elements can be moved when 0V is applied to each of them. If we assume that it takes 0,1 ms to move one element (average response time of common ERF) then we need 0,3 ms to move all black pins shown in figure 7. It doesn't matter how many elements each row has. Control time of an array depends on number of rows only.

Control method described above can be applied to array manipulator drive actuated in both ERF valve modes – single and multilayer.

2-link planar manipulator

The manipulator scheme is shown in Figure 8. The manipulator consists of two rigid links connected by two joints (*A* and *B* in Fig. 8, *a*). Joint *A* is equipped with an actuator, while joint *B* is unactuated and equipped with a brake (Fig. 8, *b*) based on ERF application to regulate the friction force inside the contact zone of the joint. It consists of a housing secured to the first and a pin secured to the second links. There is an electrode attached to the pin and the other electrode attached to the housing of the brake. The volume of the brake is filled with ERF. Fluid is used as an active element of the brake to control the number of DOF of the kinematical pair *B* by applying voltage to electrodes in the contact zone of its elements. Generated friction force is proportional to the applied voltage. If the voltage is high enough, the ERF becomes a solid forming from revolute kinematical pair *B* to the immobile joint by braking its elements. Joints are also equipped with encoders to provide position control of the links.

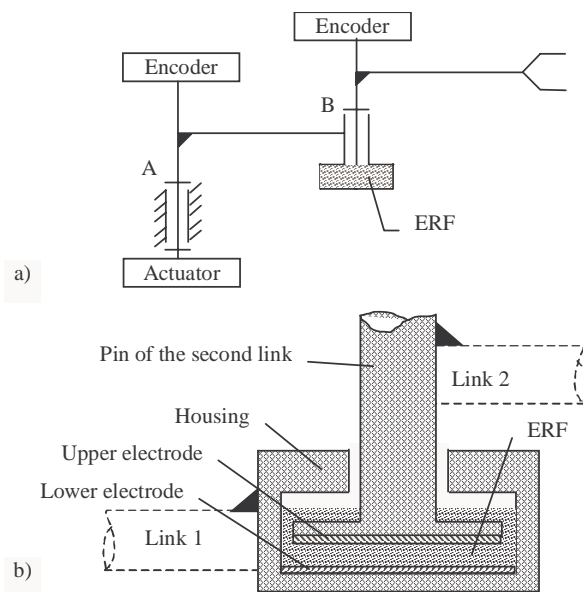


Fig. 8. Manipulator design: schematic (a) and kinematical pair brakes (b)

The experimental model of manipulator (Fig. 9) was designed. The experiments confirmed effectiveness and high performances of the active kinematical pairs based on ERF exploitation. Here torque is only at joint 1 and accelerations of links 1 and 2 are equal. Joint 2 is also passive (unactuated and free). Torque is applied only to joint 1, and accelerations are different for both links. There are two main problems in under actuated manipulator design – braking of passive joints and output link position control. Passive joints can be locked or unlocked by brakes of various kinds. Usually electromagnetic brakes are used. They allow achieving great braking torque, but are of high dimensions and large time constant.

The experience described above allowed us to develop a manipulator based on active material application for passive joint braking and propose its control. Active material - electrorheological fluid (ERF), whose main advantages are fast response 0.1 – 1 μsec order (time constant) and possibility to control its viscosity continuously to almost solid-state, is used for braking joints. Active joint control via application of acceleration instead of torque is proposed.

The dynamic model of such a type of manipulator is known as:

$$\begin{bmatrix} T_1 \\ 0 \end{bmatrix} = \begin{bmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{bmatrix} \begin{bmatrix} \ddot{\theta}_1 \\ \ddot{\theta}_2 \end{bmatrix} + \begin{bmatrix} c_1 \\ c_2 \end{bmatrix}; \quad (19)$$

where θ_1 corresponds to the angle of the link-1 with respect to x axis, θ_2 corresponds to the angle of link-2 with respect to link-1, T is the torque applied to the joint 1, c – vector of Coriolis, centrifugal, gravitational and frictional forces and M is the 2 x 2 inertia matrix of the manipulator.

In our case members of equation (19) are the following:

$$\begin{aligned} M_{11} &= I_1 + m_1 d_1^2 + I_2 + m_2 l_1^2 + 2m_2 l_1 d_2 \cos \theta_2 \\ &+ m_2 d_2^2 \\ M_{12} &= I_2 + m_2 l_1 d_2 \cos \theta_2 + m_2 d_2^2 \\ M_{21} &= M_{12} \\ M_{22} &= I_2 + m_2 d_2^2 \\ c_1 &= -2m_2 l_1 d_2 \dot{\theta}_1 \dot{\theta}_2 \sin \theta_2 - m_2 l_1 d_2 \dot{\theta}_2^2 \sin \theta_2 \\ c_2 &= -m_2 l_1 d_2 \dot{\theta}_1 \dot{\theta}_2 \sin \theta_2 - m_2 l_1 d_2 (\dot{\theta}_1 + \dot{\theta}_2) \times \\ &\dot{\theta}_1 \sin \theta_2 \end{aligned} \quad (20)$$

where m_1, m_2 are masses of link 1 and link 2, respectively; I_1, I_2 are mass moments of inertia of link 1 and link 2, respectively; d_1 is the distance of the gravity center of link 1 from the vertical axis of joint A; d_2 is the distance of the gravity center of link 2 from the vertical axis of joint B.

Solving the second of equations (1) for $\ddot{\theta}_2$ we obtain the relationship for manipulator control by acceleration $\ddot{\theta}_1$ as input.

$$\ddot{\theta}_2 = \frac{I_2 \ddot{\theta}_1 + m_2 l_1 d_2 \ddot{\theta}_1 \cos \theta_2 - m_2 l_1 d_2 \dot{\theta}_1 \dot{\theta}_2 \sin \theta_2}{I_2 + m_2 d_2^2} + \frac{m_2 d_2^2 \ddot{\theta} + -m_2 l_1 d_2 (\dot{\theta}_1 + \dot{\theta}_1) \dot{\theta}_1 \sin \theta_2}{I_2 + m_2 d_2^2} \quad (21)$$

In order to confirm the feasibility of the proposed method, the motion and control of two degrees of freedom manipulator is simulated using appropriate software “Simulink”. Equation (21) is used to simulate motion of the robot whereas $\ddot{\theta}_1$ is used as input signal (acceleration ddttheta1) for the link 1. Some experimental results are presented in figure 9.

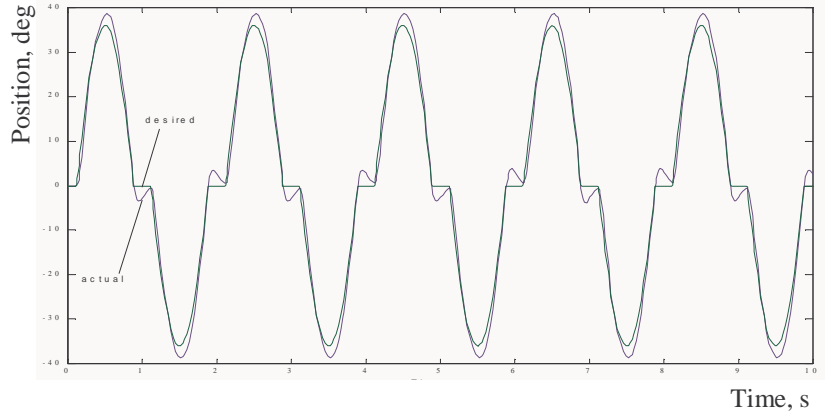


Fig. 9. Position of end-effector of manipulator

To design a close-loop control scheme, proportional (PID) controller is proposed to use. Brakes that contain ERF are faster (respond in milliseconds), lightweight and more fail-safe than electromagnetic brakes. Stepper motor was used to actuate the joint-1 and angular acceleration of the rotor of stepper motor to control the motion of link-1. Simulation of motion of the robot shows that using acceleration, as the control signal at the active joints and using the PID controller is effective combination to achieve desirable movement of the end-effector of the manipulator.

3 EXPERIMENTAL RESEARCH

Series of experiments were conducted in order to investigate practical usage of ERF in manipulator drive. Experiments were conducted at Kaunas University of Technology Institute of Piezomechanics.

Experimental research in shear mode

Special equipment was made to investigate ERF in shear mode. This equipment allows changing viscosity of ERF by changing strength of electric field.

Experimental setup consists of: housing, piezoelectric bimorph, tank for ERF, electrodes, digital signal generator, data acquisition system (DAQ) and source of high voltage (DC voltage changer). Piezoelectric bimorph consists of three layers: two piezoelectric plates, separated by one carbon layer. Piezoelectric bimorph was used to generate transversal oscillations and as sensor at the same time.

Sequence of experiment: one piezoelectric plate of bimorph is actuated by alternating signal from sweep generator. Bimorph starts oscillating thus deforming other piezoelectric plate of bimorph. This plate generates electrical signal which form and amplitude depends on damping rate of ERF between electrodes. Damping rate can be changed by changing voltage between electrodes 5 and 6 thus changing viscosity of ERF.

Figure 10 shows resonant amplitude-frequency curves of piezoelectric sensor under different voltage applied to ERF. It can be observed that under strong electric field curve is not as sharp as under 0V. This behavior of system was expected because of damping of ERF. Experimental results are presented graphically in figure 10. When voltage between electrodes increase to 250 Volts (strength of electric field is 833 V/mm), it is hardly noticeable change of frequency and amplitude. If voltage increases from 250V to 500V amplitude-frequency change is clear enough. It means that polarization of dielectrical parts of ERF is weak under electrical field strength lower than 1000 V/mm.

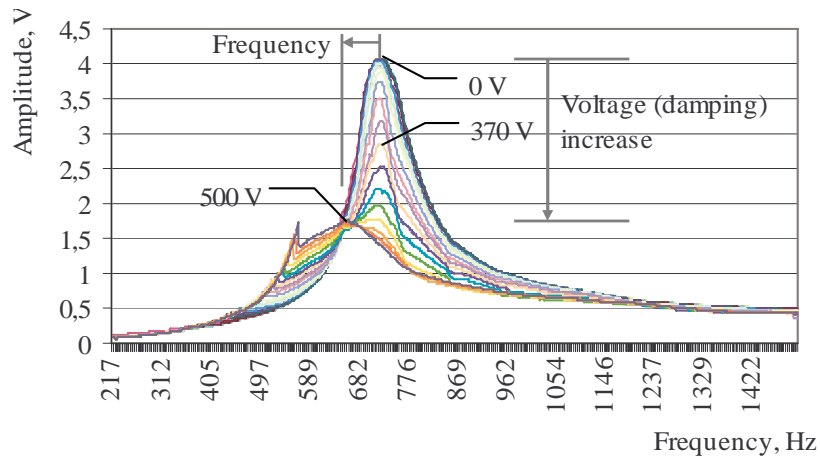


Fig. 10. Resonant amplitude-frequency curve

One of critical points of using ERF in practice is high voltage supply to electrodes of drive. In all our experiments voltage was supplied by wires. That makes design of drive complicated. Especially if it is important to make drive as small as possible. More complicated is wires connection to electrodes in case if electrodes have to be movable. Voltage supply by wires can not alter movement of electrodes. Considering this issue special modification of manipulator drive was made in Institute of Piezomechanics. Drive works in shear mode as well but electrodes of such drive are stable and don't move. It means that there are no wires connected to electrodes. Working principal of mentioned drive is presented in figure 11.

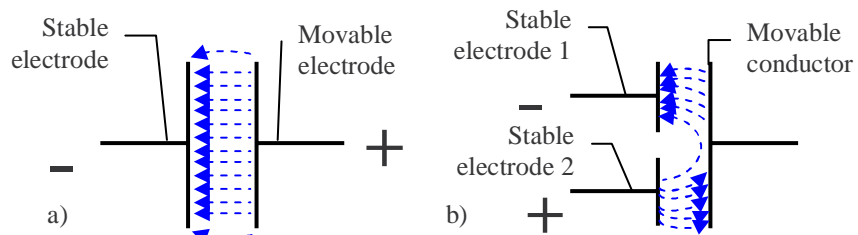


Fig. 11. Electrical field lines. Different drive design (a and b)

Figure 11 *a* shows case when lines of electric field go from one electrode to another directly. 11 *b* shows lines of electrical field that connects electrodes via

separate conductor. In this case voltage is supplied to both positive and negative electrodes (stable electrodes) by wires and no wires are connected to movable electrode. Thus movable electrode can be moved without any restrictions caused by wires or other direct connections. That makes design of such drive much simpler.

Here it needs to be mentioned that such drive design has one serious problem – it needs approximately two times higher voltage than drive shown in figure 11 *a*. This is because distance between electrodes is bigger.

Experimental research in squeeze mode

The point of experiment in squeeze mode was to move two parallel electrodes towards and backwards each other periodically and to investigate suitability of such drive design. Experimental device of such experiment is shown in figure 12. Electrodes of this device are placed in a way that is similar to 3 x 3 array drive described in previous sections. Positive (upper) and negative (lower) electrodes are perpendicular to each other and are separated by net made of insulator material. Upper-movable electrodes are made of aluminium foil and are attached to elastic membrane. Lower electrodes are made of copper and are stable. Maximum amplitude of displacement of upper electrodes is restricted by aluminium foil and it is ~1 mm.

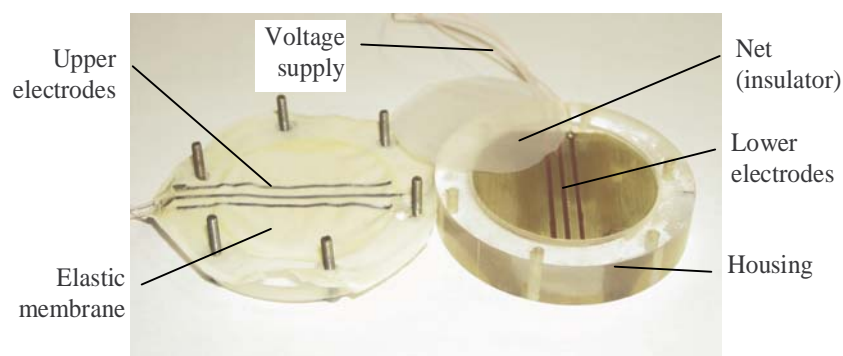


Fig. 12. Experimental device. Squeeze mode

Plastic net was necessary to separate electrodes and to avoid direct contact. Free flow and contact of ERF to both electrodes was necessary as well. After some experiments that were conducted using above mentioned device and more similar devices, it was found that squeeze mode is design-effective but functionless for array manipulator. It was shown by experiments that non-homogenous ER fluids are not suitable in cases when area of electrodes and

maximum distance between them is small enough (~ 10 sizes of average ERF particle).

Experimental research of ERF in valve mode

Valve mode is one of the most promising modes of ERF work. As it was mentioned at the beginning of this work, valve mode let us get active hydraulic system with controllable medium. Experimental research of valve mode was conducted in Institute of Piezomechanics at Kaunas University of Technology. There are two cases of valve mode considered in theoretical research of this work. Attention to multi-layer valve was concentrated in experimental research. Figure 13 shows experimental setup of multi-layer valve. It consists of pressure device (pump), manometer, multi-layer valve (one channel), high voltage source and ampermeter.

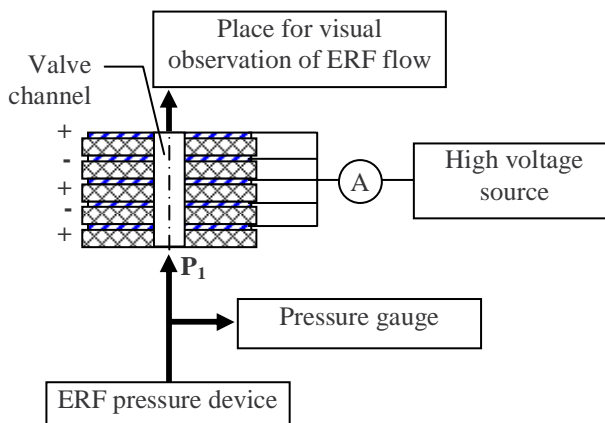


Fig. 13. Experimental setup of multi-layer valve

This experiment was conducted in following sequence. ERF is pressurized by special device thus forcing ERF to flow into valve channel until it is possible to observe it visually. Then high voltage (fixed value) is connected to valve electrodes locking ERF in channel. After that pressure starts to increase and it is possible to see this in scale of pressure gauge. Pressure is slowly increased until ERF flow is possible to observe visually again. Values of pressure and current are recorded then. Voltage is switched off thus unlocking ERF and negative pressure was created in order to pump ERF back to tank. Experiment is repeated under higher voltage (higher strength of electric field) applied to

electrodes. Therefore it is possible to get table of values of pressure difference at valve input and output under different voltage.

Valve itself consists of number of copper plates separated by insulator material. Every second layer of electrodes is connected to positive pole and rest layers are connected to negative pole. Working principle is based on effect when particles of ERF are connected in chains under strong electric field. Two different modifications (see Table 1) of multi-layer valve were used for experiment.

Table 1

Parameters of two multi-layer valves

Parameter	Valve No 1	Valve No 2
Thickness of insulator between electrodes	0,6 mm	0,25 mm
Number of electrodes in valve channel	11	11
Diameter of channel	0,6 mm	0,5 mm

It was observed that maximal pressure difference which ERF can hold is as twice as bigger when relation between channel diameter and distance between electrodes is $\sim 1:1$, than in case of $1:2$. This difference can be explained using graphical representation of electric field lines in multi-layer valve channel. It can be assumed that particles of an ERF closes valve channel effectively just in case when lines of electric field fills all across channel. In this case strength of electric field is almost equal in all volume of a channel (Fig. 14 a). Otherwise (in case of relation $1:2$) strength of electric field is concentrated close to edges of a channel and it is weak at the center of a channel thus letting ERF to flow through this weak zone (Fig. 14 b).

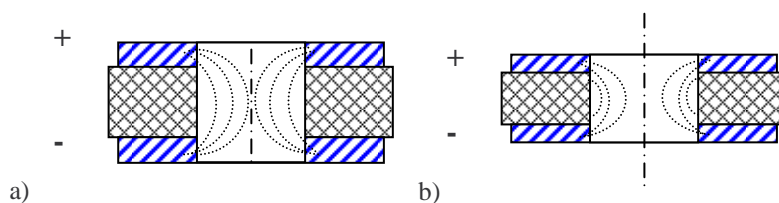


Fig. 14. Lines of electric field under different relations between diameter of channel and distance between electrodes: a) 1:1; b) 1:2

The design of multi-layer valve is simple and similar technology that is developed in electronic industry can be used. Number of layers and geometry of the valve depends on desired effect.

4 RESEARCH OF ERF BEHAVIOR IN SMALL GAPS

Using ERF in drive, based on multi-layer valve or shear mode is not traditional as it has small gaps and clogging problem can arise due to structure of ERF. Experimental investigation using ERF in small gaps was conducted in Kaunas University of Technology. Investigation shows that the smaller gap is the stronger effect we observe. But disadvantage is that minimum size of a gap is limited by size of ERF particles because of clogging problem. Average size of single ERF particle is up to $30\ \mu\text{m}$ usually and particles align themselves in chains along lines of electric field. It was assumed that small gap is approximately 10 times of a single particle size in order to work valve properly. Particles of ERF form chains in electrical field. The stronger are field the stronger are chains. In case of small gap and strong electric field chains remain even if voltage is switched off. This phenomenon is more critical in valve mode because there are no moving parts. The only moving element is media of valve and that is ERF. In case of clog such valve loses its function. Investigation also showed that clog can be removed mechanically only.

Special equipment was made in order to watch behavior of ERF visually. It was possible to scatter ERF clog using high frequency mechanical oscillations. Principle scheme of experiment is presented in figure 15. Figure 15 a shows ERF clog between electrodes and figure 15 b shows clog scattering by oscillating piezoelectric actuator.

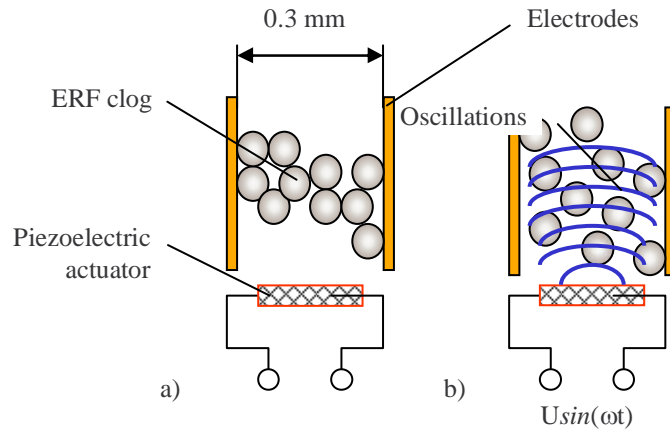


Fig. 15. Principal scheme of experiment: a) ERF clogs between electrodes; b) clog scattering by high frequency oscillations

Experimental device consists of two electrodes made of aluminium foil pasted on glass plate. Distance between electrodes is 0,3 mm. High voltage is supplied to electrodes by wires. Piezoceramic actuator is attached to glass plate. Piezoceramic element can be actuated by high frequency sweep generator. Glass plate is used to watch and record behavior of ERF visually. Microscope with possibility to record movie by digital camera was used. Experimental results are presented in figure 16.

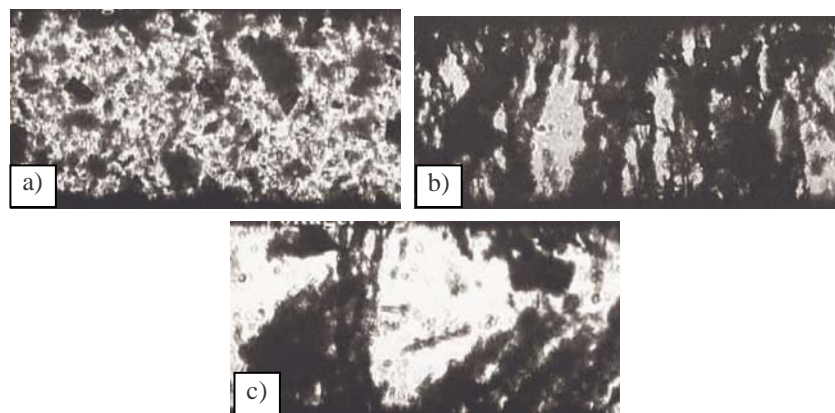


Fig. 16. ERF behavior: *a* – no electric field; *b* – clog after actuation; *c* – clog scattering

It was observed that influence of clog to work of a drive is not so sharp in cases when electrodes are movable like in shear mode. The bigger is amplitude of oscillations the less is influence by ERF clogs.

5 PRACTICAL IMPLEMENTATION OF RESEARCH RESULTS

Principal of array manipulator drive can be used not for manipulation of objects only. It also has potential implementation into information technologies (IT). For example, it can be used in interactive display system that will facilitate access for visually impaired people to the modern information technology world. It is part of the ItactI project financially supported by the European Commission (EC). The new tactile graphical display could make it possible to further integrate the visually impaired population into the information society, improving their access to many resources, including internet pages, by offering a more natural and effective display. As it is mentioned above, part of this research was done under International Project "Smart interactive tactile

interface effecting graphical display for the visually impaired" IST-2001-32240 ITACTI (2001-2004). Project partners: De Montfort University (UK), Smart Technology Group Ltd. (UK), Metec AG (Germany) and Associazione Nazionale Subvedenti (Italy).

Tactile display that exists on market usually consists of 70 – 80 special cells, placed in one row. Such display can be connected to computer via special devices in order exchange information between user and machine. Blind persons use special tactile code, created by French Luji Braille. Standard Braille cell consists of six elements: two columns and three rows. Such cell is presented in figure 17.

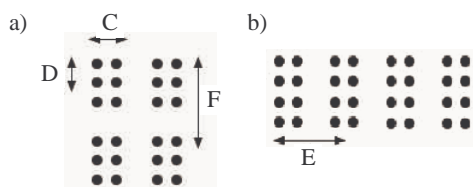


Fig. 17. Fragment of tactile Braille cells

Two more elements can be added to standard cell to display special symbols (Fig. 17 b). Distances C, D, E and F are different in various countries and are presented in table 2.

Table 2

Dimensions of Braille cell

C, mm	D, mm	E, mm	F, mm	Pin height	Pin diameter
2,03 – 3,25	2,03 – 3,25	5,38 – 9,78	9 – 13	0,46 – 0,81	1,4 – 1,9

With reference to research of this work few prototypes of tactile display drive were created at Institute of Piezomechanics. These prototypes work in shear mode.

Figure 18 shows one of prototypes. It has 3x3 array that consists of 2.5 mm diameter pins. Distances between centers of pins are 5 mm. Also it was made another prototype which is smaller and there 0,7 mm pins were used. That allowed reducing distance between pins down to 2 mm.

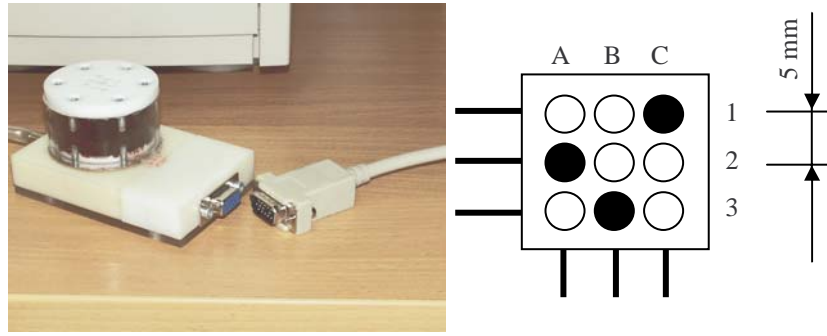


Fig. 18. Prototype of tactile display that works in shear mode

The distributed manipulation device is proposed for data transmission in a tactile way. Electrorheological fluid is used for the manipulating elements motion control. The device can be used to provide people with visual disabilities access to the information on a computer screen.

Electrorheological fluid (ERF) has the fundamental property to become solid-state under electric field action. This phenomenon allows controlling the stiffness and damping of the structure, which can be changed dynamically by applying high voltage.

The main drawback of classical ERF valves when applied in $m \times n$ array manipulators (e.g. for manipulating Braille dots) is high requirements of the accuracy of the components and whole assembly due to small gaps ($\sim 0.1 \dots 0.2$ mm) between pin and cylinder, filled with ERF. This drawback can be eliminated by new multi-layer valve design when axial electric fields are used.

CONCLUSIONS

1. It is confirmed by experimental research that squeeze mode is not suitable for array manipulation. Multilayer valve is proposed instead. Principal design of manipulator drives is suggested as well. This leads to the reduction of the device complexity and increases its reliability, and even durability.
2. Control method of manipulator drive such as multiplexing of voltage and pressure is created by *Smart Technology Ltd.* and proposed in this work. This method allows avoiding separate connection of control signal to each of the manipulator elements therefore simplifying technology of production of such manipulator.
3. Design and analysis of dynamic models of array and planar manipulators drives has been done. Equations, which describe the motion of the

manipulating elements, have been derived and Simulink model for the investigation of its dynamics has been created on its base. The primary results of the pin dynamics have been obtained illustrating the influence of the main factors upon the motion of the pin.

4. Advantages and disadvantages of using electrorheological fluids in thin layers are investigated in this work. Most common problem – clogs of particles of fluid is described. New solution for solving clogging problem is created and proposed as well. One of the solutions can be implementation of high frequency oscillations, generated by piezoelectric actuators. It is confirmed by experimental research.

5. The method of actuator control via application of acceleration instead of torque and new type of brakes in passive joints, which uses the electrorheological fluid as the element of brakes is proposed. Brakes that contain electrorheological fluid are faster (respond in milliseconds), lightweight and more failure-safe than electromagnetic brakes.

6. Practical implementation of array manipulator drive is presented in this work. The distributed manipulation device is proposed for data transmission in a tactile way. The device can be used to provide people with visual disabilities access to the information on a computer screen.

7. It is observed that implementation of ERF in commercial applications is complicated until homogenous and giant-effect electrorheological fluids are developed and used in array manipulator drive.

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MANIPULATORIAUS PAVAROS SU ELEKTROREOLOGINIU SKYSČIU KŪRIMAS IR TYRIMAS

REZIUOMĖ

Mokslinis darbas atliktas Kauno technologijos universitete pagal Europos Sąjungos projektą IST-2001-32240 ITACTI (“Interactive Tactile Interface” – interaktyvi taktilinė sąsaja), kurio vienas iš daugelio uždavinių yra elektoreologinio skysčio panaudojimas matricinio manipulatoriaus principu veikiančios interaktyvios taktilinės sąsajos (taktilinio ekrano), skirtos akliesiems, technologijos sukūrimui.

Šiame darbe tiriama galimybė panaudoti aktyviąją medžiagą – elektoreologinį skystį tam tikruose manipulatoriuose – matriciniame ir plokščiojo judesio. Pirmame skyriuje pateikiamas matricinių ir plokščiojo judesio manipuliatorių tipų apžvalginis tyrimas, aptariami jų panaudojimo praktikoje klausimai. Antrame skyriuje pateikiamas elektoreologinio skysčio veikimo principo paaiškinimas, jo savybės, galimi veikimo režimai. Taip pat sudaryti manipuliatorių elementų dinaminiai modeliai ir juos aprašančios lygtys, parodomas dinaminių modelių judesio modeliavimas. Trečiame skyriuje pateikiami eksperimentiniai tyrimai ir jų rezultatai. Tiriama galimybė taikyti tokį skystį siekiant sukurti pavaras ar valdymo metodus, kuriais būtų galima keisti mechanizmų laisvės laipsnių skaičių arba mechanizmų struktūrą. Ketvirtame skyriuje apžvelgiamos elektoreologinio skysčio panaudojimo plonuose sluoksniuose problemos, analizuojamos jų priežastys, pateikiami galimi sprendimo būdai. Penktame šio darbo skyriuje pateikiamas galimas

praktinis tiriamojo darbo rezultatų taikymas. Darbo pabaigoje suformuluotos išvados, pateiktas literatūros sąrašas, autoriaus mokslinių publikacijų sąrašas. Rašant darbą buvo naudotasi monografijomis, žurnalų publikacijomis, straipsniais, patentų duomenų bazėmis ir Internete rasta medžiaga, taip pat Kauno technologijos universiteto Pjzomechanikos instituto bei užsienio kompanijos „Smart Technology Ltd.“ (Didžioji Britanija), pateikta mokslinė informacija. Atlikti eksperimentiniai tyrimai, pagrįsti teoriniais skaičiavimais bei teoriniu modeliavimu, naudojantis programiniu paketu „Matlab Simulink“. Eksperimentams naudotas „Smart Technology Ltd.“ sukurtas elektoreologinis skystis, o jam tirti panaudota moderni signalų gavimo ir apdorojimo sistema.

IŠVADOS

1. Teoriniais ir eksperimentiniais tyrimais nustatyta, kad nehomogeninio ERS tempimo-gniuždymo režimas netinkamas matricinio manipulatoriaus ar taktilinio ekrano gamybai. Tuo tarpu šlyties režimu galima pasiekti didžiausią ER efektą. Tačiau efektyviausią rezultatą ER efekto stiprumo ir konstrukcijos technologiškumo atžvilgiu, galima pasiekti panaudojant pasiūlytą daugiasluoksnių vožtuvo principą.
2. Sukurtas ir pasiūlytas matricinio manipulatoriaus valdymo metodas – įtampos ir slėgio paskirstymas, nereikalaujantis kiekvienam elektrodai atskirai prijungti valdymo signalą, kas leidžia supaprastinti manipulatoriaus konstrukciją ir jo gamybos technologiją, o ypač tinka daugiasluoksniui vožtuvui.
3. Naudojantis sudarytais matricinio ir dviejų grandžių perteklinio judrumo manipuliatorių su ERS pavarų judesio dinaminiais modeliais, su jų išėjimo grandžių judesius aprašančiomis lygtimis nustatyta, kad ER efektas didesnis tuo atveju, kai skystis naudojamas plonuose sluoksniuose. Mažinant tarpą tarp elektrodų efektas didesnis, negu tuo atveju, kai atstumas didinamas, bet tuo pačiu didinama įtampa tam pačiam elektros lauko stiprumui išlaikyti.
4. Iširta, kad naudojant ERS plonuose sluoksniuose, t.y. esant nedideliems tarpams tarp pavaros elektrodų, tarp jų gali susidaryti ERS dalelių kamštis. Šiai problemai spręsti pasiūlytas naujas metodas, pasitelkiant aukšto dažnio mechaninius virpesius. Šiems virpesiams sukelti pasiūlyta panaudoti pjezoelektrinius žadinimo elementus.
5. Dviejų grandžių perteklinio judrumo manipulatoriaus valdyme ir tikslesniam grandžių stabdymui pasiūlyta naudoti efektyvius elektoreologinius stabdžius, veikiančius šlyties režimu.
6. Praktinio taikymo pavyzdžiui pateikti buvo pasirinkta matricinio manipulatoriaus principo panaudojimo alternatyva. Panaudojant daugiasluoksnių vožtuvo režimu veikiančio matricinio manipulatoriaus

principą, galima kurti technologiškai paprastą taktilinio ekrano pavarą, kuriai valdyti pakanka vieno žadinimo elemento – ERS.

7. Atliekant eksperimentinius tyrimus nustatyta, kad siekiant geresnių rezultatų reikia atlikti tyrimus su sukurtais ir intensyviai tobulinamais homogeniniais ERS, kurie neturi nusėdimo problemos. Taip pat reikia atlikti tyrimus su ERS, kuriems valdyti reikia gerokai mažesnės elektros įtampos nei šiuo metu rinkoje naudojamiems skysčiams.

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