427. Analysis of piezomotor driver for laser beam deflection

V. Juska[a], L. Svilainis[b] V. Dumbrava[c]
Kaunas University of Technology, Kestucio st. 27, LT-44312 Kaunas, Lithuania
e-mail: [a] *vladas.juska@ktu.lt,* [b] *linas.svilainis@ktu.lt,* [c] *vytautas.dumbrava@ktu.lt*

(Received 15 January 2007; accepted 10 March 2007)

Abstract. A mechanical laser beam deflection using piezoactuator is analyzed in the paper. Wide angular range was required therefore mechanical mirror positioning using a multilayer piezoceramics friction drive configuration was chosen. The paper reports on research results of the deflection system parameters. Dynamic and static motion parameters such as angular speed, breaking displacement, positioning repeatability and angular resolution have been analyzed. For this purpose the measurement equipment have been designed and manufactured. Analysis of breaking characteristics has revealed that breaking angular displacement is dependant on driving voltage. Conducted positioning repeatability experiments indicate that the relative error between steps was about 1 %. Analysis of the complex electrical impedance of the piezoactuator over frequency range under varying load conditions was conducted. The equipment for measurement of electrical parameters has been described. Experimental research results of the actuator complex impedance are presented.

Keywords: laser beam deflection, piezoactuator driver design, complex impedance, angular displacement measurement.

Introduction

Development of optical technology has created a demand for devices capable of steering a laser beam at high speed. Optical scanners have received acceptance in various applications as optical wireless, inter-satellite links, target acquisition in military platforms, large scale imaging, 3-D displays, optical data storage as well as holography and interferometry [1, 2]. Every application requires a different set of parameters. Several methods [3, 4] can be applied to scan a laser beam: mechanical, electromechanical, liquid-crystal, acousto-optic and electro-optic methods.

Mechanical methods use moving mirrors and are slow due to inertia. Microelectromechanical machines are useful for a laser beam scanning, their speed is still limited. Electro-optic [5] scanning is based on solid state ferroelectric devices and offers faster scanning. But speed is limited by the voltage and generally is limited to one dimension. The Polarization-Multiplexed Optical Scanner manipulates the polarization of an incoming laser beam in a digital fashion and allows achieving 3-D scanning.

The goal of the work is to design low-cost, moderate- speed and high-accuracy two-dimensional laser beam deflection driver for micro-vibrations imaging using laser interferometry.

Driver structure

Application of piezodriver mechanical scanning system allows increasing the scanning accuracy and reducing the inertia. Piezoelectric motors [6, 7] are regarded as an attractive alternative for an electric actuator owing to high torque at low speed, high power/weight ratio, high efficiency and small size as well as high control resolution. In addition, piezodriver is cheaper than other sophisticated high accuracy technologies. Therefore it was decided to use a mechanical steering, where the angular positioning is accomplished by means of the piezoelectric micromotor. Proposed structure is presented in Fig.1.

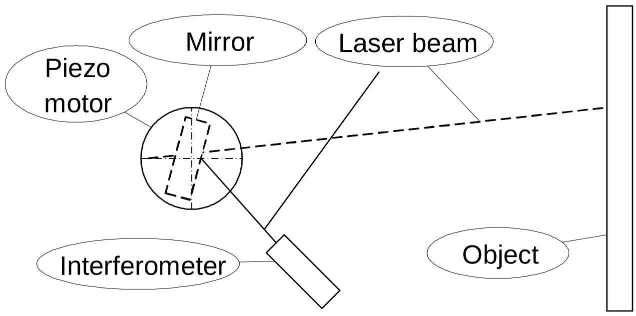

Fig. 1. Mechanical beam deflection for interferometry

Optimal distance to the object, recommended by interferometer manufacturer is 60 mm. This implies that wide scanning angles range is needed in order to scan sufficient area of the investigated object. Laser beam is scanned by changing the angular position of the mirror located in the beam path. Such structure allows achieving wide scanning angle and high accuracy.

Motion parameters measurement

Dynamic and static motion parameters [8] such as angular speed, breaking displacement, positioning repeatability and angular resolution have been analyzed. For this purpose the measurement equipment have been designed and manufactured.

Measuring equipment. Optical encoder achieving 600 pulses per revolution has been adopted for angular motion measurement. For angular displacement measurement interpolation between encoder marks an optopair with light curtain was used (Fig. 2).

Optopair signal was calibrated basing the encoder marks. The curtain size and the optopair beam are selected to create linear response between closest available encoder marks. Optopair intensity is converted to voltage signal by transimpedance amplifier. Refer to Fig. 3 for motion parameters measurement system structure. The converted and amplified analog voltage of optopair light intensity level has been registered by means of A/D converter and processed by microprocessor together with encoder logic levels and piezomotor control signals. The acquisition of the aforementioned signals was synchronous in order to maintain the temporal response registration jitter low. Then collected data was transmitted to host personal computer for storage and further processing. The interface was used for host PC communication

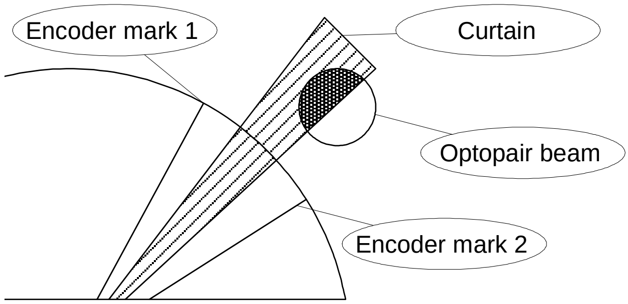

Fig. 2. Angular position between encoder marks interpolation

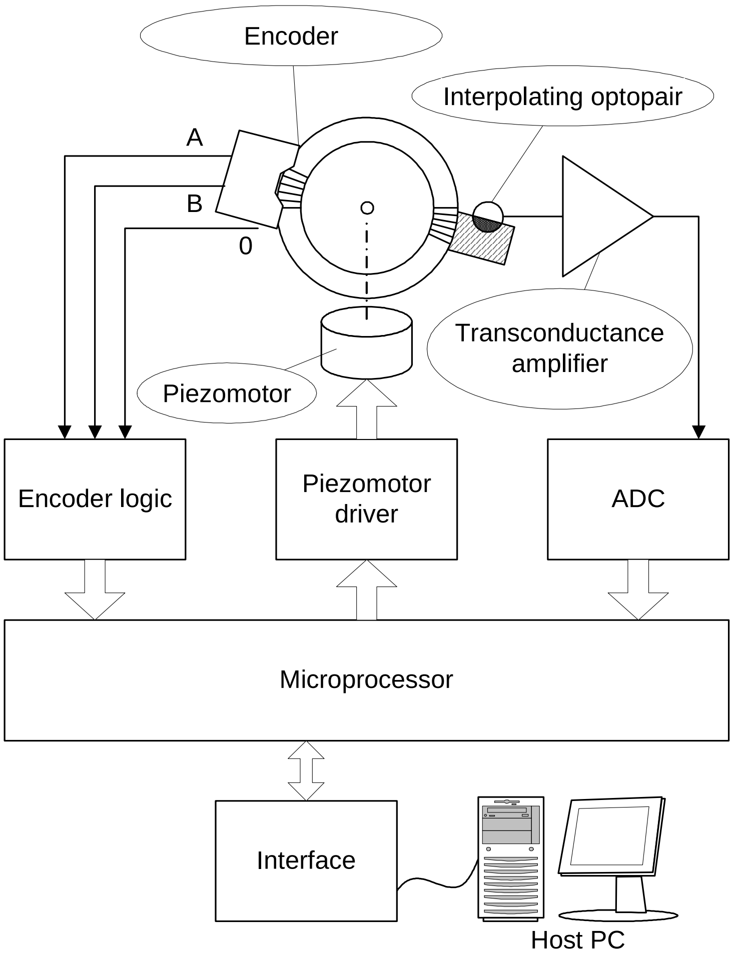

Fig. 3. Motion measurement equipment structure

Data collected on host PC was subsequently processed to obtain motion parameters.

Angular speed. The essential investigation related to motor motion is the angular speed. In Fig. 4 we provide the rotation speed dependence on piezomotor excitation voltage for clockwise (CW) and counterclockwise (CCW) direction.

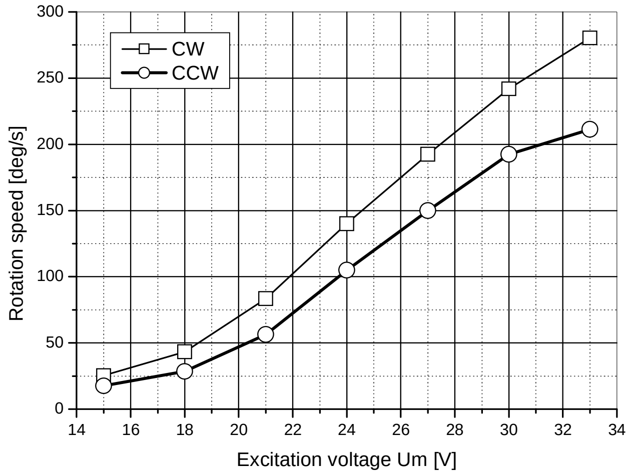

Fig. 4. Rotation speed versus excitation voltage

The angular speed relation to driving voltage magnitude experiments indicate that 280 deg/sec angular speed has been achieved at 33 V driving voltage in CW direction. The speed obtained in CCW direction was slightly lower and at same excitation voltage has reached 220 deg/sec.

Braking distance. Braking distance was measured as post excitation motion of the mirror. Experimental results of braking distance measurement when excitation voltage was varied in the range of 15 – 33 V are presented in Fig. 5.

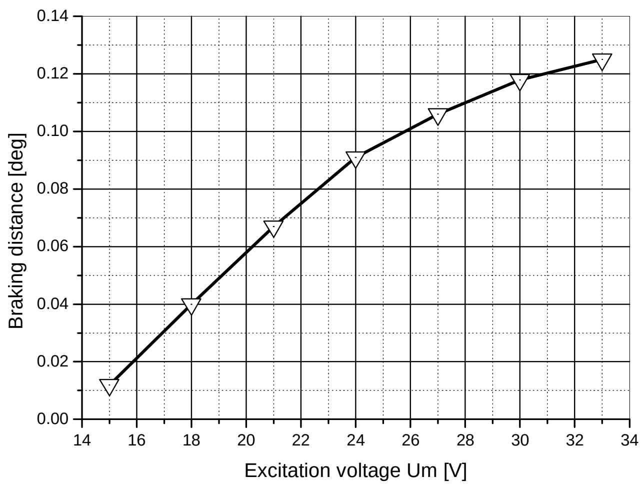

Fig. 5. Braking distance versus excitation voltage

Braking characteristics analysis has revealed that braking angular displacement is dependant on driving voltage. The relation is nonlinear. At 33 V excitation signal magnitude was 0.125 degrees.

Positioning accuracy. As it was indicated above the angular speed is excitation voltage dependant. But in such case the rotation moment is unavoidably modified which in turn complicates the control electronics. It would be much easier to control the motion speed by modifying only temporal parameters of excitation signal. Strictly speaking, by forming shorter pulse train which is responsible for angular motion. Inertial system properties would maintain the achieved angular speed during pause between the packets and average speed is controlled by packet duty cycle. In order to inspect the duty cycle variation linearity on speed control corresponding experiments have been carried out. The influence of driving pulses on angular positioning dynamics has been analyzed. The angular position has been constantly monitored while varying the number of applied driving pulses. The number of driving pulses has been varied from 2 to 8. Time diagrams of angular displacement are presented in Fig. 6.

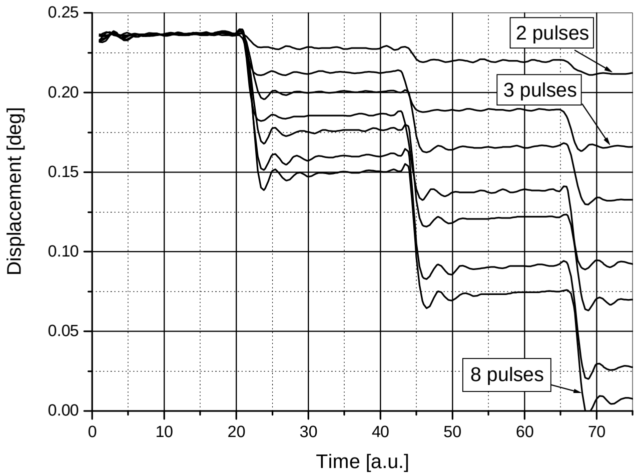

Fig. 6. Angular displacement as a function of pulse train size (2 to 8)

It is evident that transient response influences the obtainable step size. The results indicate that angular speed is pulse packets duty cycle dependant and is increasing with duty cycle increase.

Same results can be used for resolution of angular displacement estimation. Since available resolution is the major advantage of piezoelectric mirror scanning potential resolution estimation is important. In order to estimate this resolution the same experimental results have been processed in order to estimate the percentage uncertainty and achieved angular displacement. Obtained results are listed in Table 1.

Table. 1. Angular displacement versus pulse train size

	8 pulses	7 pulses	6 pulses	5 pulses	4 pulses	3 pulses	2 pulses
$\Delta\varphi_{vid}$, deg	0.066	0.063	0.052	0.0454	0.033	0.023	0.008
0.3 deg/ $\Delta\varphi_{vid}$	4.52	4.78	5.81	6.60	9.12	13.22	37.5
σ $\Delta\varphi$/ $\Delta\varphi_{vid}$, %	3,8	3,8	3,2	3,3	3,3	5,8	7.4

The ratio 0.3 deg/$\Delta\varphi_{vid}$ indicates (0.3 deg is the angular encoder resolution) that angular resolution can be increased. But it is necessary to note that all measurement points have been synchronized to angular encoder marks. Therefore if unsynchronized mode is used (no angular encoder) the displacement uncertainty would increase. It can be noticed that relative uncertainty is increasing with pulse train size reduction. This is because an error in displacement is introduced with increasing the angular speed due to transient process. But at minimal displacement the error is defined by purely random factors. Or system inertia influences the first pulses in a train.

Positioning repeatability experiments have been carried out in order to estimate the achievable accuracy. Results of fourteen realizations of the same three steps have been used for analysis. Results for displacement obtained are presented in Fig. 7.

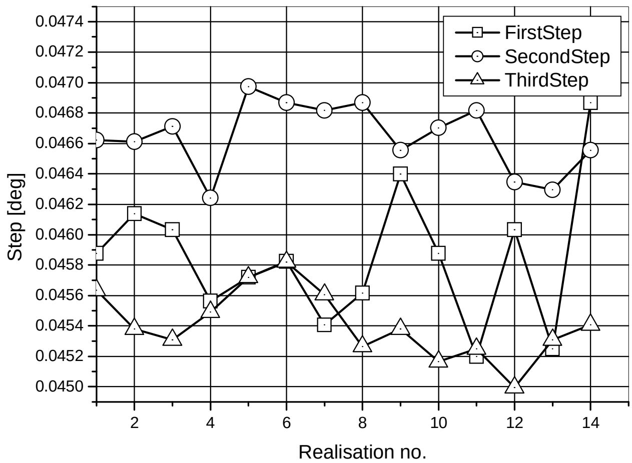

Fig. 7. Angular displacement repeatability for 14 realizations

The accumulated data was processed to obtain the standard deviation of the position repeatability. Results are listed in Table 2.

Table. 2. Angular displacement repeatability

	1-st step	2-nd step	3-rd step
$\Delta\varphi_{vid}$, deg	0.046	0.047	0.045
$\delta\ \Delta\varphi$, %	-0.26	1.47	-1.2
$\sigma\ \Delta\varphi$, %	0.98	0.49	0.50

Average step size was 0.046 deg at 7 driving pulses. Relative error between steps was about 1 %.

Electrical parameters measurement

It might turn out that piezoelectric actuator is driven at voltage levels beyond the limit for which the material was nominally characterized. In general driving piezoceramics at high power levels introduces nonlinearity [9]. Also the thermal effects will influence the mechanical (so the electrical) parameters of the actuator. In the small signal region piezoceramics are typically linear, isothermal and adiabatic [10]. When the same materials are driven at higher drive levels the thermal conditions can change considerably. This will change the electrical matching conditions of actuator and driver, causing the driving efficiency decrease. By monitoring the actuator impedance [11] change the optimal deflection system driving conditions can be selected. Therefore the analysis of the complex electrical impedance of the piezoactuator over frequency range under varying load conditions was carried out.

Measuring equipment. The equipment for measurement of electrical parameters has been developed [12]. The system utilizes the I-V mode of impedance measurement. Electrical impedance measurement system structure is presented in Fig. 8. System includes excitation signal generator based on direct digital synthesis and resulting waveforms acquisition units. Two simultaneous 10 bits analog-to-digit converters are available. Data can be streamed at

100 Ms/s into two independent 256k samples deep memory banks. The system control and data transmission to the host PC is performed via a high speed USB2 interface.

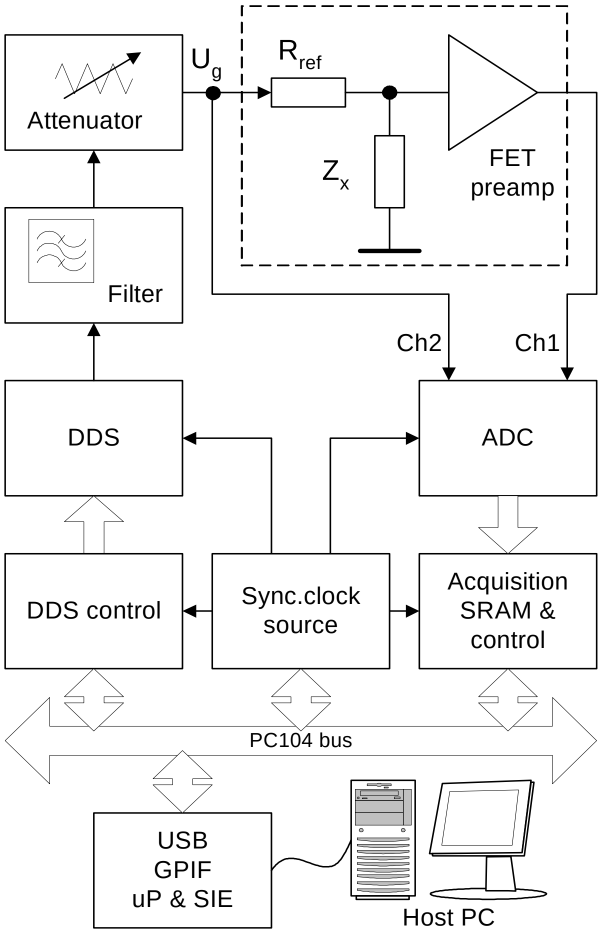

Fig. 8. Electrical impedance measurement system

For signal containing only single frequency for excitation sine wave correlation technique can be applied for signal amplitude and phase extraction.

The amplitude and phase estimation in the presence of noise turns out to be difficult. The use of sine-fitting technique can significantly reduce the noise. The fitting function is:

$$u(t) = U_c \cos(2\pi ft) + U_s \sin(2\pi ft) + U_0 \qquad (1)$$

where U_c and U_s are the in-quadrature amplitudes, U_0 is the DC component and f is the excitation frequency. This method is useful if the excitation frequency is not known. It should be noted that impedance measurement system (Fig. 8) is using common synchronization clock source both for excitation signal generation and waveform acquisition. In this case the sine fitting can be simplified since excitation signal frequency and acquisition sampling rate ratio is exactly known. The reference frequency will be insignificant. Furthermore, if signal containing only single frequency is used for excitation then sine wave correlation (SWC) technique [12] can be applied to extract the signal amplitude and phase by using cosine and sine signals for correlation. Fitting the function (1) to the signal as a set of M samples, $y_1 \ldots y_M$, acquired at a frequency f_s at time instances $t_1 \ldots t_M$ then is accomplished as:

$$U_c = \frac{\sum_{m=1}^{M}\left[\cos(2\pi f t_m)\cdot y_m\right]}{\sum_{m=1}^{M}\left[\cos(2\pi f t_m)\right]^2}, U_s = \frac{\sum_{m=1}^{M}\left[\sin(2\pi f t_m)\cdot y_m\right]}{\sum_{m=1}^{M}\left[\sin(2\pi f t_m)\right]^2} \quad (2)$$

Then the measured signal magnitude and phase is:

$$U = \sqrt{U_c^2 + U_s^2}, \varphi = \arctan\left(\frac{U_s}{U_c}\right) \quad (3)$$

The impedance Z_x is calculated from voltages in channels 1 and 2 (Fig. 8):

$$Z_x = \frac{\overline{U}_1}{\overline{U}_2} R_{\mathrm{ref}} . \quad (4)$$

Experimental study results of the actuator complex impedance are presented below.

Electrical impedance measurement results. The impedance measurement is needed for the impedance variation monitoring. Refer to Fig. 9 for impedance measurement example in the case of changing load conditions

As it was mentioned before the excitation voltage will change the level of the actuator coupling to mechanical system. Due to such effect impedance change is expected. Refer to Fig. 10 for the corresponding experiment results.

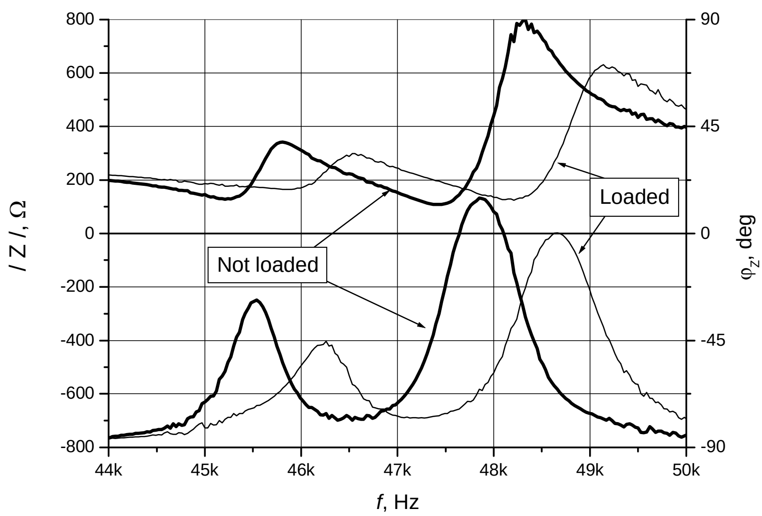

Fig. 9. Electrical impedance variation with load

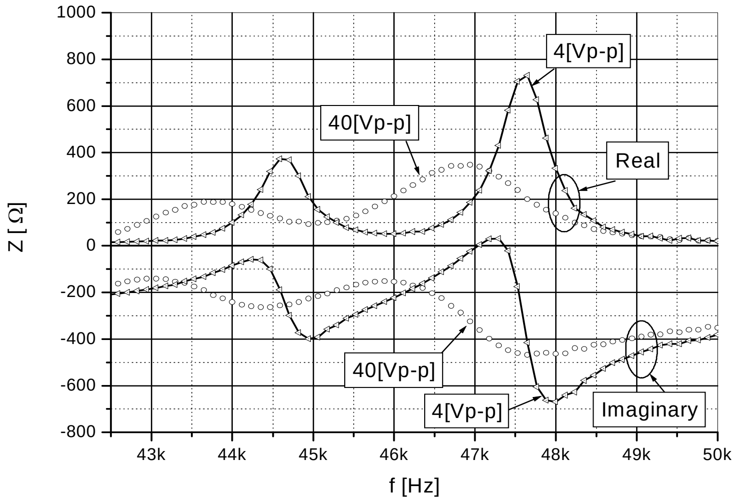

Fig. 10. Electrical impedance variation with excitation voltage

Changing the deflection actuator excitation voltage impedance variation is sufficient. Such changes have to be taken into account when designing the matching circuit for actuator excitation and driver electronics.

Summary

Experiments indicate that 280 deg/sec angular speed has been achieved at 33 V driving voltage in clockwise direction. Counterclockwise speed was slightly lower and at same excitation voltage has reached 220 deg/sec. At the same driving voltage braking displacement was 0.125 degrees. Experimental results of positioning repeatability indicate that average step size was 0.046 degrees at 7 driving pulses. Results of electrical impedance monitoring reveal that varying load and excitation conditions influence the electrical impedance of the actuator. These changes have to be accounted in design of driving electronics and matching circuits.

Acknowledgment

This work was carried out under project “Research and Development of the Multi-Degree-of-Freedom Mechatronics Displacement Generation/Measurement Systems With Nanometric Resolution” of High-Tech Development program supported by Lithuanian State Science and Studies Foundation.

References

[1] **Khan S., Riza N.** High Speed Coarse-Fine Laser Beam Steering Module for Polarization-Multiplexed Optical Scanner. Lasers and Electro-Optics Society, (2003), p.11-12

[2] **Goto H., Imanaka K. and K. Uchino.** Piezoelectric actuators for light beam scanners. Ultrason. Technol., Vol. 5, (1992), p. 48–51

[3] **Mateus C.** Monolithically MEMS Laser Beam Steering Fabricated on AlGaAs System. COMSOL, (2007), p.1.

[4] **Marshall G. F.** Optical Scanning. (Marcel Dekker, New York 1991).

[5] **Scrymgeour D. Koc B. et.al.** Hybrid Electrooptic and Piezoelectric Laser Beam Steering in Two Dimensions. Journal of lightwave technology, Vol.23 (2005), p. 2772-2777

[6] **Giraud F. et.al.** Analysis and Phase Control of a Piezoelectric Traveling-Wave Ultrasonic Motor for Haptic Stick Application. IEEE Trans. On ind. App., Vol. 40, (2004), p. 1541-1549

[7] **Seo J., Hur J. and Sung H.** A Novel Ultrasonic Motor Using Orthogonal Bimorphs. IEEE Trans. On magnetics, Vol. 43, (2007), p. 1413-1417

[8] **Arrivabeni V. et. al.** A Novel Type of Piezoelectric Minimotor for Linear Displacements. IEEE Ultrasonics symposium (2003), p. 1774-1777.

[9] **Sherrit S., Bao X. et. al.** Characterization of Transducers and Resonators under High Drive Levels. IEEE International Ultrasonics Symposium, Atlanta, GA, (2001), p.1-4.

[10] **Xu J., Grant E. et. al.** Drive Circuit for a Mode Conversion Rotary Ultrasonic Motor. IEEE, (2005), p.1588-1592.

[11] **Svilainis L., Dumbrava V.** Measurement of complex impedance of ultrasonic transducers. Ultragarsas, Vol. 62, (2007), p. 26-29.

[12] **Dumbrava V., Svilainis L.** The Automated Complex Impedance Measurement System. Electronics and electrical engineering, Vol. 76, (2007), p. 59-62.