CONTRIBUTIONS ON THE STUDY OF THE TRANSIENT PROCESS FOR ELECTROMECHANICAL ACTUATORS WITH LIQUID

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Abstract. *In this article, the experimental stand and the methods used to obtain the theoretical and experimental characteristics which represent the unit step response for electromechanical actuators with volatile liquid are presented. The thermal conditions for the volatilisation process and the influence of the temperature range on experimental data are considered. The used volumes of active liquid cause the variations of the obtained unit step response. For this reason, the various volumes of active liquids are investigated and the operating characteristics resulted are represented. These types of electromechanical actuators with liquid can find their applications in various areas, which reclaim the small size, low power of actuation and short response time. Also, in the chemical industry of medicines most of the time it is necessary to use devices supposing the achievement of simple from the constructive viewpoint, with small sizes and small costs, based on simple principles of working and easy to handle.*
Keywords: *electromechanical actuators, bellows, volatile liquids, transient process, and unit step response.*

Introduction

Today, in the domain of electromechanical actuation, there appeared different types of models that operate using methods of conversion of various source of energy.
An actuator is defined as a device with which the energy obtained from the classical physical effects and phenomena is changed into mechanical energy, necessary for linear or rotation actuation of various mechanisms.
Generally, the structure and operating of most actuators are based on the following technologies: electromagnetic actuation, magnetostrictive actuation, piezoelectric actuation, electrostatic actuation, hydraulic actuation, pneumatic actuation, and electrothermal actuation or electrochemical actuation.
One distinct class is the class of electrothermal actuation that includes such technology developments as sealed capsule expansion actuators, dual layer bimorph actuators, shape memory alloy actuators and pneumatic actuators.
Therefore, it would be highly desirable to have a new and improved actuator, and the method of using it, which by resorting to low electric currents, capable of micro-miniaturization and which present very rapid actuation times.
In this context, the electrothermal actuator can operate with one or two phases and is actuated, principally, by forces and effects, which are proportional to the variation of active substance volume, in boundary conditions concerning the temperature [1].
The element, on which the movement is transferred, can be a piston [2], an electrical chamber (bellows) [3] or an elastic membrane [4].
An experimental electromechanical actuator consists of an elastic chamber (bellow), which operates like a sealed capsule expansion actuator with volatile liquid like ether, alcohol or freon.
When the chamber is exposed to thermal medium, the liquid passes on a phase change and causes inside of the bellow an upper pressure, which is used for displacement of a

driving device, by expanding and contracting the elastic bellow.

Figure 1 illustrates an electrothermal actuator which operates like a servomotor made to close or to open the valves used in hydraulic systems [1]. This servomotor it is constitute by two bellows, which is operating in opposite directions, the volatile used liquid being heated

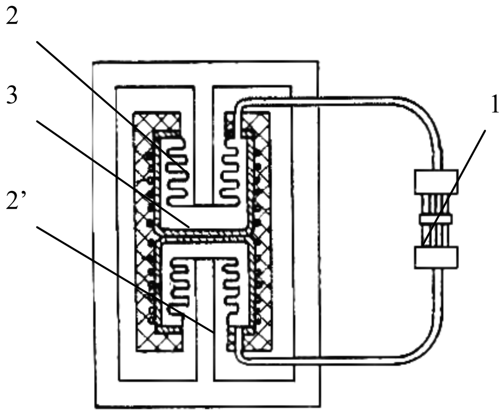


Figure 1. Electrothermal actuator:
1 – electrothermal element; 2, 2' – elastic bellows; 3 – active liquid
(Reproduced from: [3])

by an electrothermal element.

Also, the tendency of miniaturization regarding the actuation devices with small power, which have applications in domains like microrobotique and biomedicine, impose conditions about the used substances, the response's variation, the geometrical dimensions and the compatibility with the human body. It is important to find the models and to describe with accuracy the function of a great number of experimental solutions.

Considerations on the study of the transient process for an actuator with liquid

Any kind of fundamental components with a technical character, which can be connected in order to carryout of specific functions, represents a technical process.

This process is characterized by one or more input values $x_i(t)$ and a output value $x_e(t)$, and can be considered a technical dynamical system [5].

The stationary regime of a dynamical process is characterised by an output response which is constant in time. It is known that the passing from a stationary regime to another can't be instantaneous.

The period of time elapsed between two stationary regimes represents the transient process, characterized by: the period of time, the residual time constant and the dead time of the process.

Indeed, if the parameter that characterized a process is changed, than the output response is different and depends on a period of time.

This propriety is named the delayed action of process and is characterized by the residual time constant T and the dead time T_m of transient process. The identification of the function and the study of transient process are necessary for investigation of the unit step response [5], which is the variation in time of the output response due to an input unit ramp signal.

This study presents the PT_1 type element (transient process of first type), which is proportional to the residual time response, the PT_1T_m type element, which is proportional with residual time response to the dead time, and the PT_2 type element (transient process of second type), which is proportional to two residual time responses.

The PT_1 type elements, named objects of first grade are described by the next differential equation:

$$T \cdot \frac{dx(t)}{dt} + x_e(t) = k \cdot x_i(t), \qquad (1)$$

or, generally, by the differential equation:

$$a_1 \cdot \frac{dx_e(t)}{dt} + a_0 \cdot x_e(t) = x_i(t), \qquad (2)$$

where a_0 and a_1 are the differential equation's coefficients ($a_0 = \frac{1}{k}$ and $a_1 = \frac{T}{k}$), T is the residual time response of transient process and k

is the multiplication factor, known like transfer constant. The identification of the process equation supposes the determination of the differential equation coefficients by using the experimental step unit response.

The value of multiplication factor k is given by the relationship $k = x_e(\infty)$, where $x_e(\infty)$ represents the stabilized value of output response.

The residual time constant can be determined by a graphical algorithm, using the tangent line to an experimental characteristic, or the value of T can be obtained by measuring the time when the output value is equal to $x_e(t)=0,63\, x_e(\infty)$.

For an element of PT_2 type, the differential equation is:

$$\frac{d^2 x_e(t)}{dt^2} + 2 \cdot \xi \cdot \omega_n \cdot \frac{dx_e(t)}{dt} + \omega_n^2 \cdot x_e(t) = = k \cdot \omega_n^2 \cdot x_i(t) \quad (3)$$

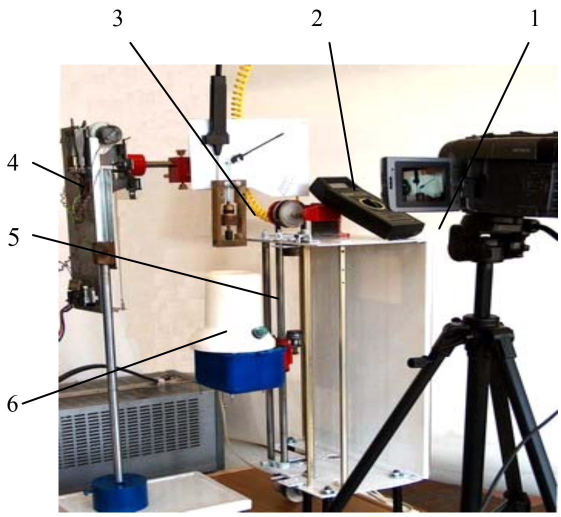
where ω_n is the natural pulsation and ξ is the damping coefficient.

Experimental identification to the transient process for an actuator with liquid

The theoretical and experimental study on unit step response was made for an electromechanical actuator constituted by a sealed bellow made from beryllium bronze, containing a volatile liquid. Two sealed heads close the bellow, one of them having a threaded extremity to adjust the position, while the other one has an axe which is passed through an orifice and which represents the movable element.

In this way, when the bellow is heated from a thermal source, it has a displacement due to the pressure of liquid from inside, which is caused by the vaporization effect of a part from liquid mass.

It is necessary to mention, that between 1996-1997, at "Stefan cel Mare" University of Suceava, some models of electromechanical actuators with liquid were made.



a.

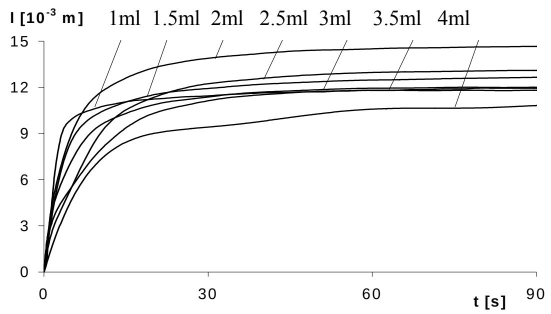
b.

Figure 2. Experimental test stand used for the study of the unit step response of the electromechanical actuator with liquid:
a – general view; b – experimental detail;
1 – video camera; 2 – thermometer; 3 – actuator;
4 – mounting bracket of the actuator;
5 – support for adjustment of the position;
6 – recipient with thermal agent.

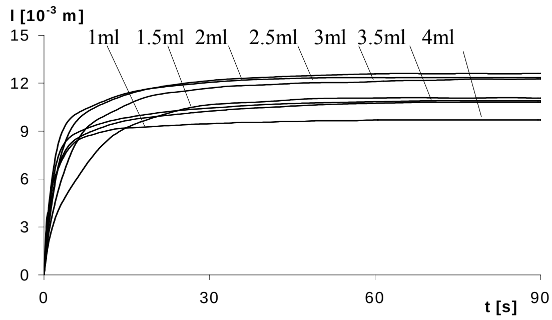
These studies were dwells on started with the elaboration of theoretical and experimental research on the models, continued with operation, function's determination, experimental application and presentation of the results in diploma projects and scientific papers [6], [7], [8].

This experimental investigations concern the on-load conditions of operating for an electromechanical actuator's model.

The main subject of the present paper is the theoretical and experimental study on the electromechanical actuators with liquid in no-load regime conditions. For this reason, an experimental test stand was made (figure 2), the step unit response was determined and the operating graphic characteristics were investigated.



a.



b.

Figure 3. Experimental characteristics *Δl(t)* for an actuator with liquid at *50°C*

a – petroleum ether; b – ethyl ether

The propulsion's element is analysed like a process with one input value represented by the temperature range $\Delta\theta$ of the heat source in time and one output value represented by the bellow's displacement value l due to the volatilisation process of the active liquid.

For identification of the operating equations and for the transient regime study, the bellow is excited with one unit step input signal to obtain the experimental unit step response. For this reason, the values of the unit step input used signal are $\Delta\theta_1=40^oC > \Delta\theta_2=50^oC > \Delta\theta_3=60^oC$.

During the experimental tests, some conditions for the physical characteristics of liquid were inferred:

- the value of boiling point of the active liquid must be into the temperature range which can appear in operating duty by bellow heating;
- must not be toxic;
- must to be easy to find and have a low cost.

The art review ([7] and [8]) shows the possibility to use the following substances like active agents: ethyl ether, petroleum ether, methyl-ethyl ether, methyl ether, dimethyl ether, divinyl ether, benzene, acetone, freon and amyl ether. In fact, for experimental tests, the ethyl ether and petroleum ether were used.

Another consideration for this study is that the volume used of the volatile liquid influences the evolution of the graphical characteristics $l=f(t)$. These volumes are: *1ml, 1.5ml, 2ml, 2.5ml, 3ml, 3.5ml* and *4ml*.

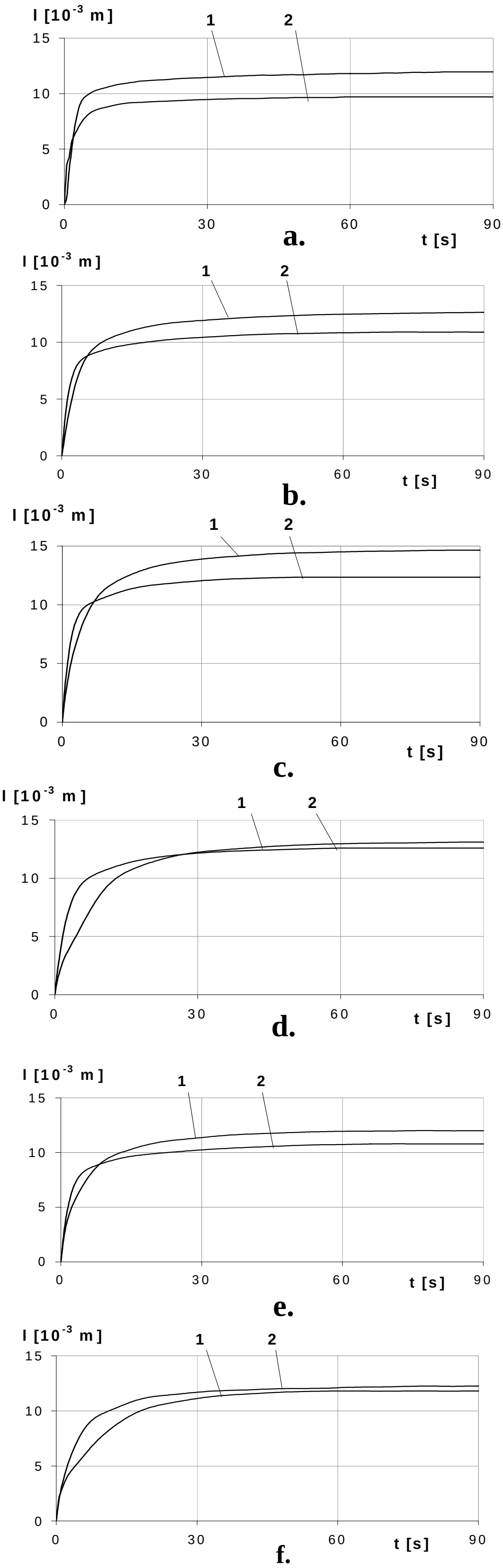
Because the period of time necessary for data acquisition is relatively small (approximate at *100 s*) and because a large number of values are needed in order to obtain an accurate unit step response, the experimental test stand was equipped with a video camera (figure 2).

In figures 3 and 4 are showed the dynamical characteristics for an electromechanical actuator with bellow, where the active liquid is ethyl ether and, by comparison, petroleum ether, when the temperature's value is 50^oC. The bellow is initially compressed and placed on a vertical position.

Also, to analyze the period of the transient process for these two liquids, in figure 4, the graphical characteristics for each used volume are represented.

Conclusions

Regarding the operating characteristics of no-load regime for an electromechanical actuator, which operates using the volatilization effect of petroleum ether and ethyl ether, the step response shows a transient process of PT_1 type, characterized by residual time response T.



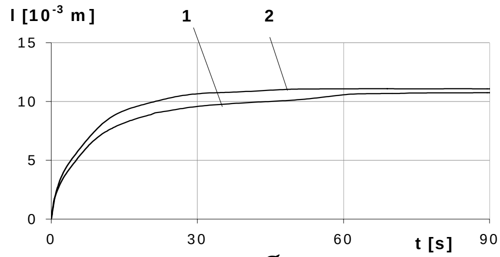


Figure 4. Variation *l(t)* for an electromechanical actuator,
with: 1 – petroleum ether and 2 – ethyl ether, where a – *1ml;* b – *1.5ml;* c – *2ml;* d – *2.5ml*; e – *3ml*; f – *3.5ml*; g – *4ml.*

This process is dependent on the volume of the used liquid.

Comparing the graphical characteristics shown in figure 4, it can be established that, for each volume of liquid, the curves *l(t)* obtained for petroleum ether has a maximum value ($14 \cdot 10^{-3} m$) greater than the one obtained for ethyl ether ($12{,}5 \cdot 10^{-3} m$).

At the same time, with the increase of the petroleum ether's volume, the graphical variations *l(t)* has the tendency to approach to the curves obtained for the ethyl ether.

This behaviour depends on the maximum value of the boiling point for petroleum ether. Under the circumstances, the volatilization process for petroleum ether is longer than in the case of ethyl ether.

The period of the transient process and the value of residual time response *T* are decreased for an actuator with ethyl ether where compared with the utilization of petroleum ether (for exemplify: *T=1,1s* at *1ml* ethyl ether and *T=3,5s* at *1,5ml* petroleum ether).

These results depend on the physical characteristics of liquids, like:

- the different values of boiling point ($34{,}5^o\ C$ for ethyl ether and between $28 \div 60^o C$ for petroleum ether);
- aspects that can influence the volatilization process at the same temperature range;
- the presence or not of the air inside of the bellow;
- the purity of liquid.

Future directions for research

Referring to future directions of research for electromechanical actuators with liquid study and experimentation, there is need of strict conditions I order to highlight point out to their real evolution.
These directions concern:
- a study on mechanical characteristics and on the influence of the geometrical dimensions;
- a study on the influence of the bellow's position;
- a study on the influence of the temperature range for testing;
- a study on the influence of the preliminary compression of the elastic bellow.

References

[1]. ROBINSON, D.W.; PRATT, G.A. Force Controllable Hydro-Elastic Actuator. In: *IEEE International Conference on Robotics and Automation.* San Francisco, April 24-28, 2000. Disponibil in World Wide Web: <http://www.ai.mit.edu/projects/leglab/>.
[2]. The Regents of The University of California. *Continuous laminar fluid mixing in micro-electromechanical systems.* Deshmukh, A.; Liepmann, D. (inventors). Int. Cl.[7] B01F 5/04. International Filing Date 2001-06-01. International Application Published under the Patent Cooperation Treaty (PCT). No: WO 01/93997 A1. 2001-12-13.
[3]. DANFOSS A/S (DENMARK). *Thermal actuator especially for fluid-flow valves.* JACOBSEN, F. ET AL. (inventors). Int. Cl.[3] G01K 5/32, F16K 31/00. UK Patent Application. No GB 2 138 937 A, 1984-10-31.
[4]. ROBINSON, D.W. *Design and Analysis of Series Elasticity in Closed-loop Actuator Force Control.* Ph.D. Thesis. Massachusetts Institute of Technology (MIT), Department of Mechanical Engineering, June 2000. Disponibil in World Wide Web: <http://www.ai.mit.edu/projects/leglab/>.
[5]. KOPELOVICI, A.P. *Sisteme de reglare automată. Metode de calcul inginereşti.* Bucureşti: Editura Tehnică, 1963, p. 67-151.
[6]. CERNOMAZU, D.; MANDICI, L.; UNGUREANU, C.; TARNOVEŢCHI, M. Micromotor solar. Brevet de invenţie RO 119563. Int. Cl. 7 F03G 6/00, din 2001-07-19, O.S.I.M., Bucureşti, România.
[7]. TARNOVEŢCHI, M.; ET AL. *Studiul funcţionării, realizării şi experimentării micromotoarelor solare cu bimetal. Contract de grant nr 6161GR/20.10.2000. Etapa 4.2.2001: Realizarea şi experimentarea de propulsoare bazate pe deformarea unor structuri solide sub acţiunea temperaturii; identificarea modelelor matematice aferente şi a factorilor de care depind funcţionarea şi performanţele micromotoarelor; finalizarea etapei cu o propunere de invenţie.* Suceava: Universitatea „Ştefan cel Mare", Facultatea de Inginerie Electrică, Catedra de Electrotehnică, 2001, p. 14-32.
[8]. GAVRILIU, M.G. *Studiu privind proiectarea, realizarea şi testarea unor noi variante de motoare solare. Proiect de diplomă.* Coordonator ştiinţific: prof. univ. dr. ing. Dorel Cernomazu. Suceava: Universitatea "Ştefan cel Mare", Facultatea de Inginerie Electrică, 1997, p. 66-87.
[9]. RUMŞISCHI, L.Z. *Prelucrarea matematică a datelor experimentale. Îndrumar.* Traducere din limba rusă. Bucureşti: Editura Tehnică, 1974, p. 9-183.