Modeling the flow regulating systems for petroleum products main pipe transport

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Abstract: -The development of new petroleum products main pipe transport installations, in order to find the optimum choice concerning their architecture and structure, supposes the modeling and simulation of the considered system. Simulation allows the generation, evaluation of instances and establishes the best solution based on performance indicators which most of the times identify with the definitive indicators of the simulated system. Simulation may be applied as well to studying petroleum products main pipe transport systems already in operation. The results of the simulation for this case emphasizes the objectives to be met within the modernization processes and the weak spots of the system ensuring the solving of problems if investments are implied for their modernization or if it is more efficient to increase expenditures for their maintenance.

Key-Words : centrifugal pump, mathematical model, flow regulating process, main pipe

1 Generalities

The paper deals with the problem of conceiving several mathematical models describing the construction and operation of petroleum products main pipe transport systems, pumping groups and the entire system. All the models refer to the transport systems where the modification of capacity parameters is realised by changing the speed of the centrifugal pump either from the main pumping station or from the intermediate stations found on the pipe route (Fig.1).

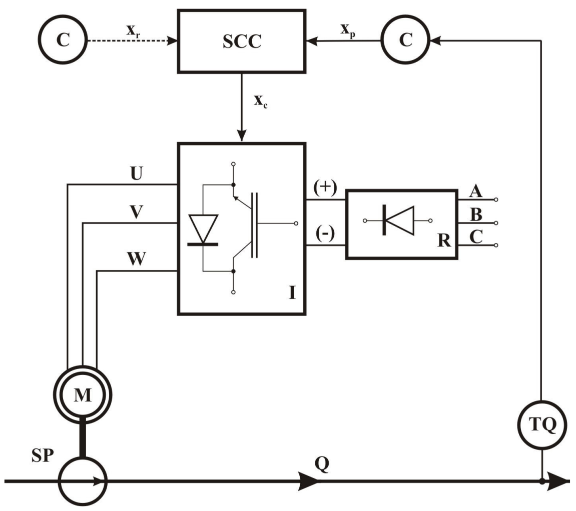

Fig.1 Automatic flow regulation basic diagram

SP - pressure source (centrifugal pump);
TQ - flow transducer;
C - - regulator;
M - asynchrony motor;
SCC - control and command system;
R - tree-phase redresser;
I - inverter;
x_p - control and command system input signal;
x_r - reference signal;
x_c - inverter command signal.

2 Main pipe modelling and simulation

In order to realise the mathematical model it is approximated that a main pipe with length L is a resistive tube. Considering all these, the stationary equation defining the pressure drop on this resistive tube is:

$$\Delta P = \frac{\rho \cdot Q^2}{2 \cdot \alpha \cdot A^2} \qquad (1)$$

where:
Q - the resistive tube flow;
ΔP - pressure drop on the resistive tube;
α - represents the flow coefficient;
A - is the area of the transversal section of the resistive tube;
ρ - represents the density of the fluid.

$$\alpha = \frac{D_H}{f \cdot \left(L + L_{eq}\right)} \quad (2)$$

where:

D_H - is the internal diameter of the resistive tube;
L - is the length of the resistive tube**;**
L_{eq} - is the equivalent length of local resistances;
f - is the friction factor determined based on relations (3).

$$\begin{cases} \text{if } R_e \le R_{eL} \text{ then} \\ \quad f = \dfrac{K_s}{R_e} \\ \text{if } R_{eL} < R_e < R_{eT} \text{ then} \\ \quad f = f_L + \dfrac{f_T - f_L}{R_{eT} - R_{eL}} \cdot \left(R_e - R_{eL}\right) \\ \text{if } R_e \ge R_{eT} \text{ then} \\ \quad f = \dfrac{1}{\left(-1.8 \cdot \log_{10}\left(\dfrac{6.9}{R_e} + \left(\dfrac{\frac{r}{D_H}}{3.7}\right)^{1.11}\right)\right)^2} \end{cases} \quad (3)$$

where:

$R_e = \dfrac{QD_H}{A\upsilon}$ - is the Reynolds number;
K_s - is the form factor characterising transversal pipes;
f_L - is the friction factor in a laminar flow regime;
f_T - is the friction factor in a turbulent flow regime;
R_{eL} - is the maximum Reynolds number in a laminar flow regime;
R_{eT} - is the maximum Reynolds number in a turbulent flow regime;
r - is the coefficient of roughness of the internal surface of the resistive tube;
υ - is the cinematic viscosity of the fluid.

The forces acting in a system are balanced for a stationary flowing regime thus obtaining the following relation:

$$\Delta P_0 \cdot A - \frac{Q_0^2 \cdot \rho}{2 \cdot \alpha \cdot A^2} \cdot A = 0 \quad (4)$$

where:

$\Delta P_0 A$ - is the active force pushing on the liquid inside the pipe;
$\dfrac{Q_0^2 \rho}{2\alpha A^2} A$ - is the reaction force due to the restriction.

In a dynamic regime the difference between the two forces is compensated by the time variation of the impulse in the system:

$$\Delta P(t) \cdot A - \frac{Q^2(t) \cdot \rho}{2 \cdot \alpha \cdot A^2} \cdot A = \frac{d}{dt}(M\omega(t)) \quad (5)$$

In relation (5), M is the quantity of liquid inside the pipe, and ω is its speed (flow). From the above relation we will consider that $M = \rho \cdot L \cdot A$ then $Q(t) = A \cdot \omega(t)$ is:

$$\Delta P(t) \cdot A - \frac{Q^2(t) \cdot \rho}{2 \cdot \alpha \cdot A^2} \cdot A = \rho \cdot L \frac{d}{dt}(Q(t)) \quad (6)$$

The measures depending on the time t in relation (6) are obtained if variations higher than the values of the stationary regime are arbitrarily given, therefore:

$$\begin{aligned} \Delta P(t) &= \Delta P_0 + \Delta(\Delta P(t)) = \Delta P_0 + \Delta p(t) \\ Q(t) &= Q_0 + \Delta Q(t) \end{aligned} \quad (7)$$

From relations (6) and (7) the following is obtained:

$$\begin{aligned} &\left(\Delta P_0 + \Delta p(t)\right) \cdot A - \frac{\rho \cdot \left(Q_0 + \Delta Q(t)\right)^2}{2 \cdot \alpha \cdot A^2} \cdot A = \\ &= \rho \cdot L \cdot \frac{d}{dt}\left(Q_0 + \Delta Q(t)\right) \end{aligned} \quad (8)$$

If the stationary regime expressed through relation (4) is extracted from relation (8), and the square term $\Delta Q^2(t)$ is neglected, the following is obtained:

$$\Delta p(t) \cdot A - \frac{\rho \cdot Q_0 \cdot \Delta Q(t)}{\alpha \cdot A} = \rho \cdot L \cdot \frac{d}{dt}\left(\Delta Q(t)\right) \quad (9)$$

In the following, if we turn to Laplace transform in initial conditions null in relation (7), we obtain:

$$A \cdot \Delta p(s) = \left(\rho \cdot L \cdot s + \frac{\rho \cdot Q_0}{\alpha \cdot A}\right) \cdot \Delta Q(s) \quad (10)$$

From the differential equation (10), the transfer function of the resistive tube is easily obtained:

$$H_{pa}(s) = \frac{\dfrac{\Delta Q(s)}{Q_0}}{\dfrac{\Delta p(s)}{\Delta P_0}} = \frac{k_p}{\tau_{pa} \cdot s + 1} \quad (11)$$

where:

k_p - is the amplification factor (k_p=1/2);
$\tau_{pa} = \dfrac{\alpha A L}{Q_0}$ - is the delay constancy of the resistive tube.

In the following we are going to present an example where we suppose that the diameter of the pipe is 8 inches. Therefore, the diameter of the pipe is $D_H = 0.2032\,[m]$ and the distance for the flow transducer is $L = 1[m]$. The diagram presented in figure 2 will be used for the determination of the friction parameter.

For the determination of this friction coefficient Reynolds number will be calculated $R_e = \frac{Q \cdot D_H}{A \cdot \upsilon}$ where υ is the cinematic viscosity of oil (API 40^0) with the density $\rho = 825\left[Kg/m^3\right]$ obtained at a $60^0 F$ temperature, Q is the flow of the pumped oil $Q = 80[m^3/h] = 80/3600\left[m^3/s\right]$.

The cinematic density of the above presented oil is $\upsilon = 3.8 \cdot 10^{-6}\left[m^2/s\right]$.

Considering these conditions Reynolds number is $R_e = 3.6642 \cdot 10^4$ indicating the existence of a turbulent flow regime. For the determination of the friction coefficient we have considered a coefficient of roughness $r/D_H = 0.00005$. Therefore from figure 1 or from relation (3) we may read / calculate the value of the friction coefficient $f = 0.023$.

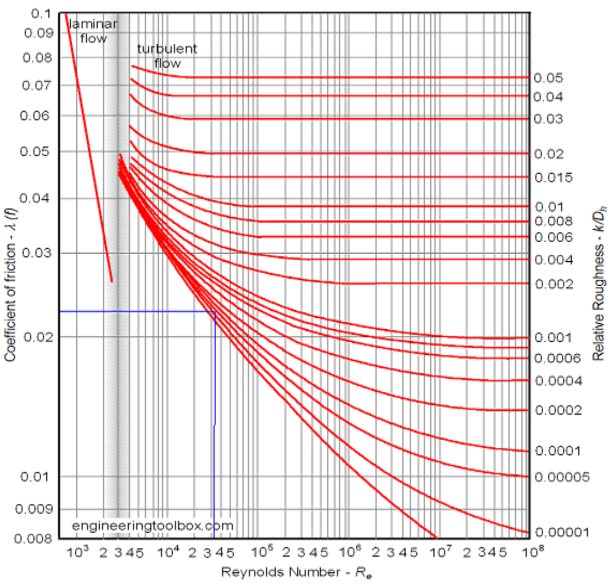

Fig.2 Friction coefficient dependencies on the Reynolds number

In these conditions, the constancies defining the mathematical model are:

$$k_P = \frac{1}{2} \text{ and } \tau_{Pb} = 13.268\left[s\right] \qquad (12)$$

Where we have considered that $L_{eq} = 0\left[m\right]$.

The transfer function (11) is used for the design of the flow regulator. For a more exact simulation formula (6) defining the dynamic regime equation of the technological pipe will be implemented using SimHydraulics toolbox in Matlab.

The block diagram of the element simulating several pipe lengths segments L and their internal structure is presented in figure 3:

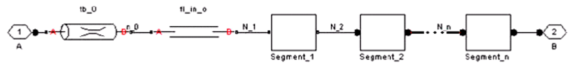

Fig.3 The mathematical model of the technological pipe using the SimHydraulics toolbox elements in Matlab

The above presented model implements relation (6), nonlinear, for each pipe segment. On the other hand, the resistive tube is defined by equation (1) and is implemented within the block presented in figure 4.

Fig.4 SimHydraulics Matlab resistive tube model

SimHydraulics Matlab block of fluid inertia is presented in figure5.

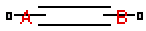

Fig.5 SimHydraulics Matlab inertia fluid model

3 Centrifugal pump modelling and simulation

The speed of the motor is considered as an input data for the mathematical model of the centrifugal pump (fig. 6). In order to determine the inlet flow necessary for the calculation of pressure, respectively that of consumed, relation (13) is used implemented by “PS Gain” block from the internal structure of the centrifugal pump.

$$Q = \frac{Q_N}{n_n} \cdot n \qquad (13)$$

where Q_N is the nominal flow of the centrifugal pump obtained at a nominal speed n_n.

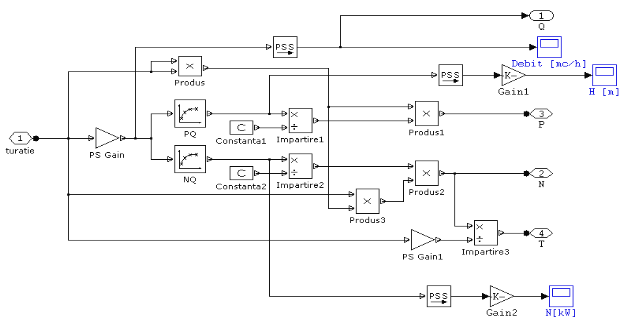

Fig.6 Internal structure of a centrifugal pump

In these conditions, the new values of the generated pressure and consumed power by the centrifugal pump will be determined with the following relation:

$$p = \frac{p^*}{n_n^2} \cdot n^2 \quad \text{and} \quad N = \frac{N^*}{n_n^3} \cdot n^3 \qquad (14)$$

On the other hand, the momentum developed by the centrifugal pump is defined by the following mathematical relation:

$$T = \frac{N}{\omega_N} \quad \text{where} \quad \omega_N = \frac{2 \cdot \pi \cdot n_N}{60} \qquad (15)$$

In order for the mathematical model of the centrifugal pump to be defined completely the SimHydraulics Matlab toolbox "pressure source" block will be installed on its outlet. These are better observed in figure 7.

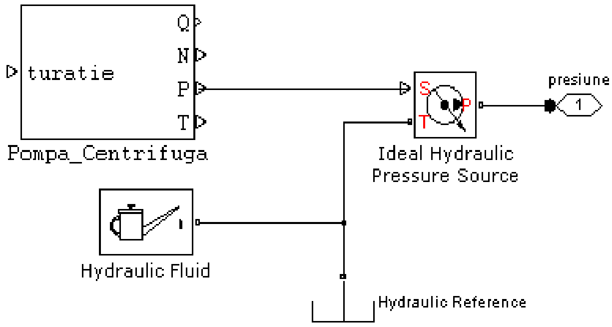

Fig.7 Centrifugal pump model using SimHydraulics Matlab toolbox blocks

Figure 8 presents laboratory model of the speed regulating system as well as the connection of the ceantrifugal pump.

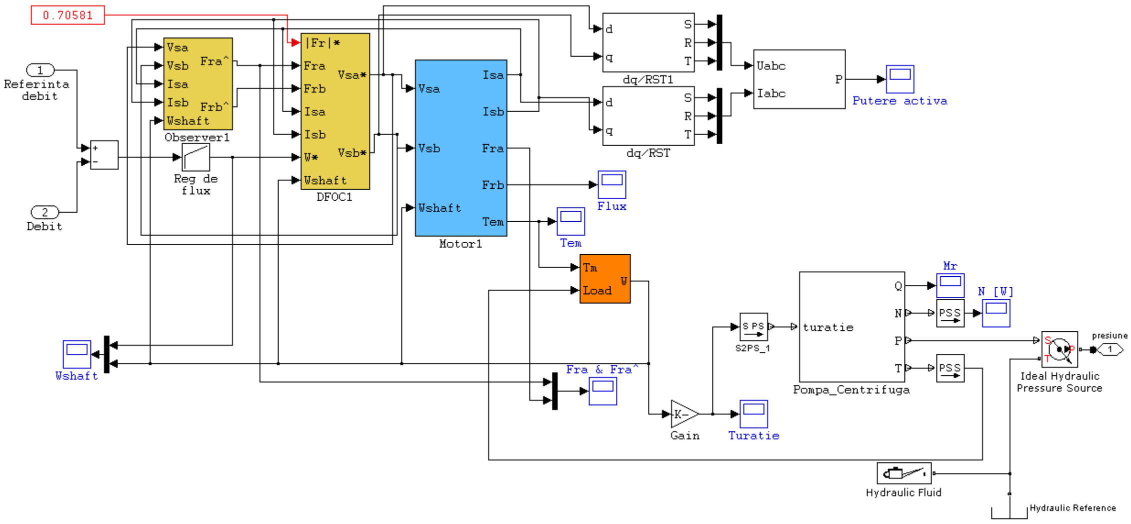

Fig.8 Speed regulating system and connection of the centrifugal pump

4 Single main pipe flow regulation system modelling

The model developed to emphasise the operation of the transport system may be used in various instances. In this case a simulation is presented for the situation in which the transportation of oil is made through one single main pipe. The flow regulating system through the modification of the speed of the centrifugal pump is presented in figure 9.

For the simulation of the flow regulating process through the modification of the speed of the centrifugal pipe, the flow Q has been given different values respectively 50, 80, 150 and 200 [m^3/h] with an operating temperature of 20^{o}C.

For the operation of the pump the 160kW power motor 1487 rpm and 3000 rpm is used.

The length equivalent to that of the main pipe for petroleum product transportation has been considered being equal to 1000m and the interior diameter of 0,2m. If the system operates at the prescribed parameters then there doesn't have to be a great difference between the imposed flow and the realised flow. Figure 10 presents the flow variation in time in the simulated transport system.

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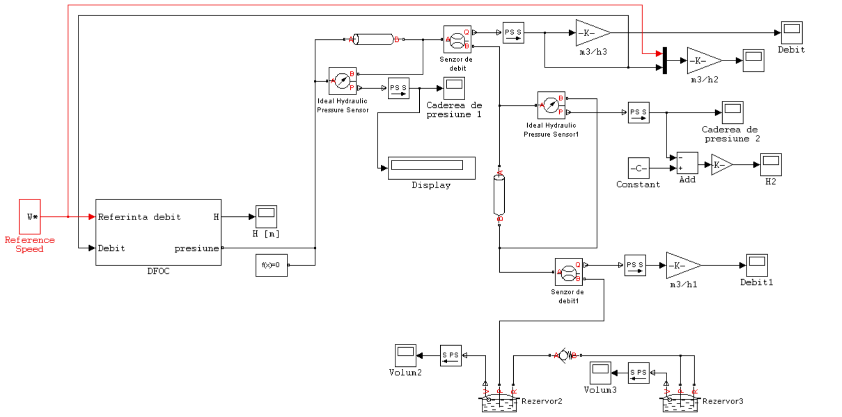

Fig.9 Flow regulating system by changing the speed of the centrifugal pump if the main trajectory is composed of one single pipe

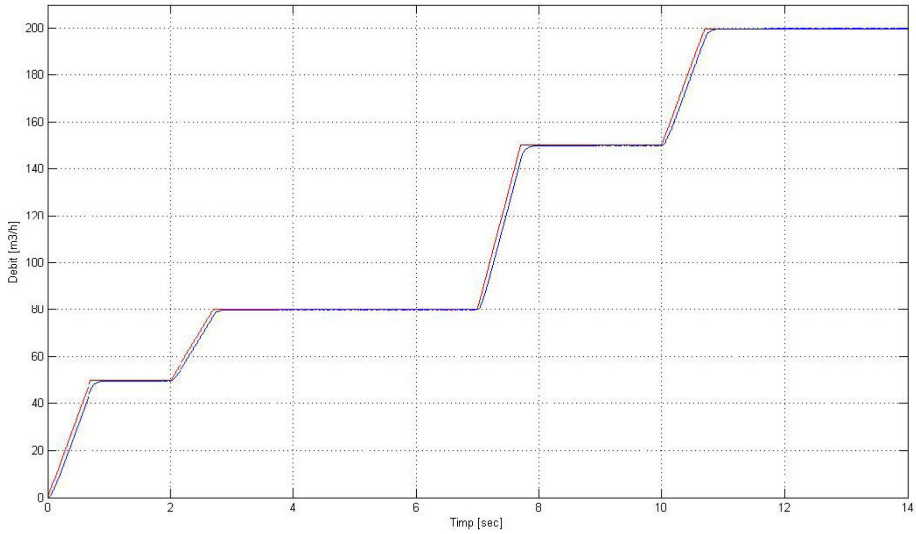

Fig.10 Time proportioned flow variation

It is observed that between the prescribed flow (in red) and the realised flow (in blue) there is a significant difference. This proves that the flow regulation system meets the functional requirements. The flow regulation system behaves as a first order a periodic system with a reduced transitional process time and a stationary error going for zero. Figure 11 presents the time variation diagram of pressure loss on the simulated pipe. It is observed that for each prescribed flow there is a pressure drop for the equivalent considered length (Table 1).

Studying the time variation of the absorbed energy by the motor in figure 12, it is observed that after its ignition, due to inertia forces, using an automated speed regulating system, there is a conversion phenomenon between the motor function and generator function.

After over passing this kind of inertial forces the actuating machine begins the motor function and the allure of the curve emphasises the regulated values of the flow through the absorbed power by it. Figure 13 represents the variation of the specific energy consumption depending on the speed of the motor.

Table 1

Presiune x 10^5 Pa	Q [m^3/h]
0.7928	50
1.2686	80
2.3785	150
3.1714	200

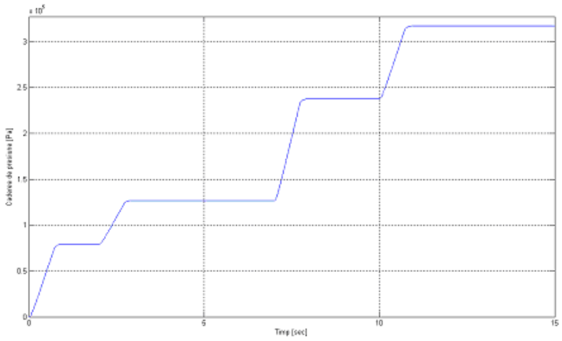

Fig.11 Pipe pressure drop variation

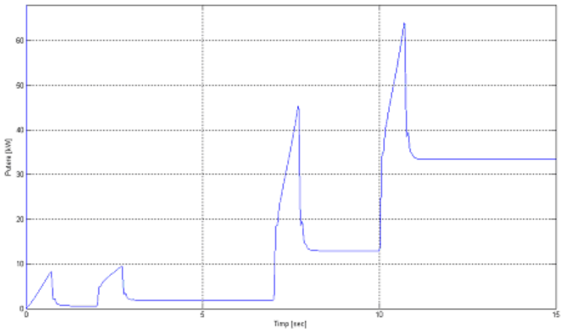

Fig.12 Motor absorbed power variation in time

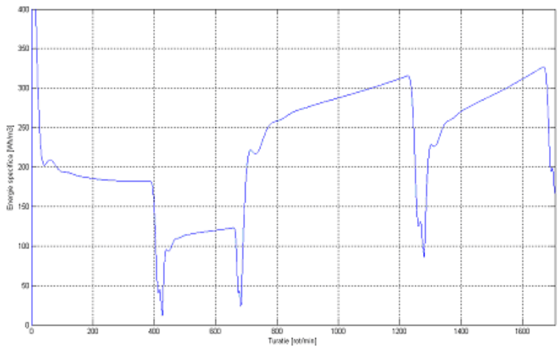

Fig.13 Variation of the specific energy consumption

5 Conclusions

When conceiving, designing and realising main pipe petroleum products transport systems, in order to find the optimum choice concerning their architecture and structure, the most modern and efficient research method is represented by the modelling and simulation of the considered system.

The simulation allows the generation of the perfect instance based on performance indicators identified to the definitive indicators of the simulated system.

For the realisation of the mathematical model of the main pipe it is approximated that the length L acts as a resistive tube.

The mathematical modelling of the centrifugal pump was realised using Matlab software application. Therefore the two characteristics of the centrifugal pump have been implemented: pressure – flow and consumed energy – flow, the input measure being the actuating asynchrony motor's speed. Based on the above mentioned facts, the speed regulating system has been conceived.

The obtained results create the premises of experimental research in Situ for the determination of their accordance with the obtained results based on the theoretical research through the implementation of mathematical models and simulations. Moreover, this method may contribute to efficiently designing flow regulating solutions for the transport of petroleum substances inside main pipes.

References:

[1] Crețu, M.D. Stan, *Transportul fluidelor prin conducte. Aplicații și probleme*, Ed. Tehnică, Bucureşti, 1984, Bucureşti, 1984

[2] Florea, J., Panaitescu, V., *Mecanica fluidelor*, Ed. Didactică şi Pedagogică, Bucureşti, 1979

[3] Flous, J.M., *La Regulation Industrielle*, Editure Hermes, Paris 1994

[4] Fransua Alexandru, *Maşini şi sisteme de acționări electice – Probleme fundamentale*, Editura tehnică, Bucureşti, 1978

[5] Fulloy, L., Popescu,D., Daufin-Tanguy G., *Modelisation, Identification et Commanda des Systemes*, Editura Academiei Romane, Bucuresti 2004

[6] Gentil, S. , Popescu, D., *Commande Numerique et Intelligence Artificielle en Automatique*, Editura Tehnica, Bucuresti, 1998

[7] Ionescu, D., Matei, P., Todirescu, A., Ancuşa, V., Buculei, M., *Mecanica fluidelor şi maşini hidraulice*, Ed. Didactică şi Pedagogică, Bucureşti, 1983

[8] Magyari Andrei, *Instalații mecanice miniere*, Editura Didactică şi Pedagogică Bucureşti, 1990

[9] Popescu Florin Dumitru, *Aplicații industriale ale tehnicii de calcul (Computer systems for industrial applications)*, Editura AGIR Bucureşti, 2009

[10] Florin Dumitru Popescu, Ilie Mitran, *The analysis of vertical transport installations considering the theory automatic systems*, Proceedings of the 8th WSEAS International Conference on System Science and Simulation in Engineering (ICOSSSE '09), University of Genova, Italy October 17-19, 2009, pp.125-130