



## ASSISTED OPTIMIZATION OF THE DYNAMIC BEHAVIOUR OF INDUSTRIAL ROBOTS

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**Abstract:** *The paper presents some new methods for analyze and optimization of the industrial robots dynamic behavior. The methods consist in on-line simulation of the real and frequency characteristics for the elements, systems and structures and compare them with the experimental characteristics obtained by data acquisition with the virtual LabVIEW proper instruments. The paper presents many virtual instruments for analyzing the hydraulic, electric and pneumatic motors, the complex systems with many closed loops, the electrical and mechanical corrections, and some complex schemas with different control laws. All the instruments have the possibility to show on-line, and to see what is happening when changing one of the functional or the constructive parameters. For analyzing and optimization the elements and the systems are presented some instruments for comparative analyze. These methods and all created virtual LabVIEW instruments can be applied in many others mechanical systems.*

**Key words:** *assisted optimization, dynamic behavior, LabVIEW instrumentation, industrial robots.*

### 1. INTRODUCTION

The virtual LabVIEW instrumentation assures reduction the apparatus number, the research time and finally, the cost. In these conditions, all stage of the research will be optimized, and reduced.

Mathematical modeling and analyses of the elements and the systems are better when will be known the dynamic behavior of all components. For this reason it is necessary to analyze all elementary transfer functions, and create proper simulation LabVIEW programs, VI [1]. With these instruments, the researchers can determine on-line, easily, the most important influence of some constructive or functional parameters, for the dynamic behavior of elements and robot's systems.

The paper presents some virtual proper LabVIEW instruments with 8.2 version, from National Instruments, USA, for the hydraulic, pneumatic and electric motors, the electrical and mechanical corrections with some closed loops. The analysis of the elements and systems was done with the elementary transfer functions by applying the different control laws. Many of the developed VI-s, what used the validated mathematical models, approximate with maximum 10 % errors the dynamic behavior of all robot's modulus. The validation of the mathematical linear models was made by comparing the real dynamic behavior, obtained by experimental research with data acquisition, with the simulated results. All the proper LabVIEW instruments offer the large possibilities to show the results, to compare in a short time the real with the simulate results, to establish very quickly the constructive or functional optimal parameters for the amplify coefficient, for the PID, PD<sub>2</sub> or for the others control laws parameters, or the place to applied the different rheological dampers. In the world the last research in this field applies the comparative analysis between the experimental research with simulation, but not used the facility of the virtual LabVIEW instrumentation. In the paper are shown some method of the optimization dynamic behavior by using: the Fourier proper

virtual analyzer; the intelligent damper system; the different closed loops or control laws; the different electrical or mechanical corrections and complex systems; the different programming delays and Fourier analyzer.

Some of the goals of the robot dynamic behavior optimization researched in this paper are: one short answer time; output signal without any vibration; one bigger value of the acceleration; one larger frequency field.

In this paper the following ways to optimize the elements, systems and structures were proposed:

- optimization the components with the small frequency – for example the linear hydraulic motor LHM, using the assisted research and the coefficients proper method;
- choice, by on-line simulation of the servo drive, the optimal parameters of all components;
- integration of some additional parts in to the mechanical schemas – for example the magneto-rheological damper;
- choice of the optimal values of the regulators, corrections and control laws parameters, by on-line simulation with transfer functions;
- applying some complex electrical and mechanical corrections, by on-line simulation;
- using the proper Fourier virtual LabVIEW analyzer to choose the optimal frequency field;
- using the new and proper schema of the intelligent damper systems.

In the world [2, 3, 4] some of these aspects were not researched in this manner, only with experimental research with not facilities offers by the experimental research with data acquisition and numerical simulation with LabVIEW virtual instrumentation.

### 2. SETUP FOR THE ASSISTED EXPERIMENTAL RESEARCH

The experimental research was made with the goal to validate the complex mathematical model, by compare

the theoretical results with the real one, and adjust the model for the LHM, for hydraulic proportional distribution, electrical drive, or for the magneto-rheological damper and so on.

For the assisted experimental research of the linear pneumatic motor LPM or of the linear hydraulic motor LHM, or for the applied damper in to the robot structure, and to validate the mathematical model and to made the numerical simulation, have been used the following apparatus: hydraulic central power, LHM with proportional distribution system,  $V$ -s of the command, control and acquisition, linear velocity transducer, accelerometers 601A01 IMI type of USA, the preamplifier for the accelerometers, the electrical stabilised 12V source, the connector for conditioning signal, the conditioning modulus SCM 5B38 type, from National Instruments USA, the apparatus for measurements of vibration from Bruel and Kjaer, didactical arm type robot, robot command amplifier, personal computer, power source, generator of function type POF-1 from KABID Poland, amplifier for the generator, type LV 102 from MMF Germany, the electromagnetic exciter type 11075 from RFT Germany, connector type CB-68 LP from National Instruments USA, acquisition board type PCI 6024E from National Instruments USA, proper virtual LabVIEW instrumentation, Fig.1 [1, 5, 6].

Virtual LabVIEW instrumentation have been made for the teoretical and experimental research with data acquisition and command of the robot. Theoretical research contents the comparative analysis of some indicial and frequency characteristics of the mathematical models for the elements, systems and structures, when was changed some constructive or functional parameters, to choose the optimal value of them in condition the respect the dynamic goals. The experimental research was made by exciting the base modulus of the robot with periodical force with different frequency, magnitude and phase and the data acquisition of the results: velocity, acceleration of the end-effector and base modulus, the excitation and damper force. In the dynamic behavior optimization one of the more important think is to optimise the dynamic compliance, the transfer function and the Fourier vibration spectrum.

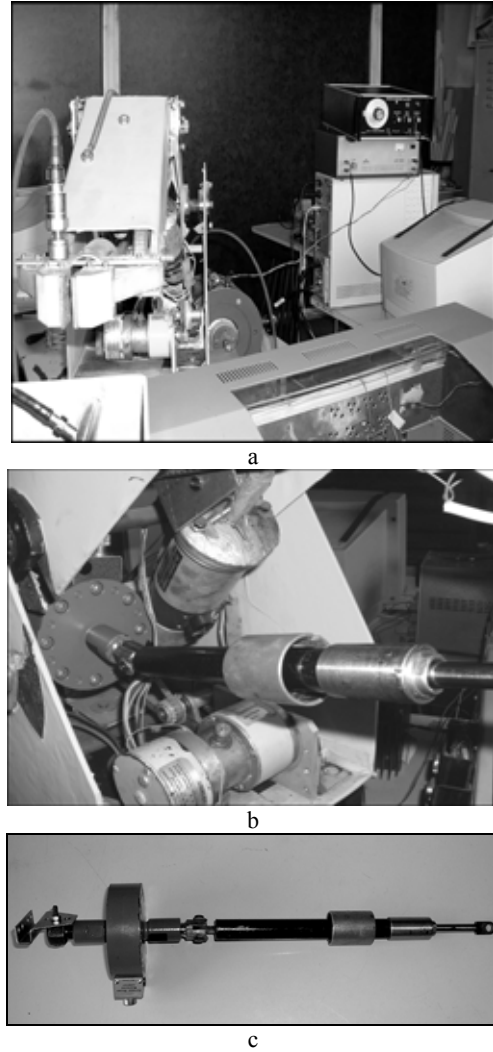
### 3. LABVIEW SIMULATION

In the stage of the numerical simulation the paper propose some mathematical models validated by experimental research. Were exemplified the mathematical model for linear pneumatic motor LPM (1) and magneto-rheological damper MRD (3), but the results of the numerical simulation with LabVIEW were made for many others components [1]:

$$Q = A_1 \frac{dz}{dt} + a_m \Delta p + \frac{V}{\chi p} \cdot \frac{d\Delta p}{dt}, \quad (1)$$

$$m \frac{d^2 z}{dt^2} + b_m \frac{dz}{dt} + F_{ax} = A_1 \cdot \Delta p; p \cdot V^\chi = \text{constant.}$$

where:  $Q$  is the air flow 20–100 [cm<sup>3</sup>/s];  $A$  – active motor area 50–80 [cm<sup>2</sup>];  $z$  – active movement 30–40 [cm];  $a_m$  – proportional gradient of loss flow with pressure 0.2–0.7 [cm<sup>5</sup>/daNs];  $\Delta p$  – loss pressure 4–6 [daN/cm<sup>2</sup>];



**Fig. 1.** The stands for the assisted research and validation of mathematical models with data acquisition: *a* – didactical researched arm type robot; *b* – the magneto-rheological damper used between the base and end-effector of the robot; *c* – damper with inductive force transducer.

$\Delta V$  – air volume of the motor 500–1 000 [cm<sup>3</sup>];  $m$  – reduced mass on the motor axis 0.1–0.6 [daNs<sup>2</sup>/cm];  $b_m$  – gradient of loss forces proportional with velocity 0.8–1.8 [daNs/cm];  $F_r$  – resisting forces 10–30 [daN];  $\chi$  – adiabatic coefficient 1.4 [-].

The final transfer function will be:

$$H(s) = \frac{z(s)}{Q(s)} = \frac{A_1}{s \left[ \frac{V}{\chi p} \cdot m \cdot s^2 + \left( \frac{V}{\chi p} \cdot b_m + m \cdot a_m \right) s + (A_1^2 + a_m b_m) \right]} \quad (2)$$

The mathematical model for the magneto-rheological damper MRD is:

$$f = c_0(x' - y') + k_0(x - y) + k_1(x - x_0) + \alpha z,$$

$$y' = \frac{1}{c_0 + c_1} [\alpha z + c_0 x' + k_0(x - y)],$$

$$z' = -\gamma |x' - y'| |z|^{n-1} - \beta (x' - y') |z|^n + \delta (x' - y'),$$

$$\alpha(i) = \alpha_3 i^3 + \alpha_2 i^2 + \alpha_1 i + \alpha_0,$$

$$\begin{aligned}
 c_0(i) &= c_{03}i^3 + c_{02}i^2 + c_{01}i + c_{00}, \\
 c_1(i) &= c_{13}i^3 + c_{12}i^2 + c_{11}i + c_{10}, \\
 k_0(i) &= k_{03}i^3 + k_{02}i^2 + k_{01}i + k_{00}, \\
 \delta &= \sum \delta_{0i} \sin(2\pi\nu_i + \varphi_i).
 \end{aligned}
 \tag{3}$$

where  $f$  is the damping force [N];  $x$  and  $y$  – primary and secondary displacement variables [m], respectively;  $z$  – internal history dependency variable of the MRD [m];  $k_0$ ,  $k_1$  – non linear internal rigidity of the MRD, [N/m] depending of the current intensity  $i$  [A];  $c_0$  and  $c_1$  – internal viscous damping parameters of the MRD [Ns/m];  $\alpha$  – internal parameter that have non linear evolution and depends on the magnetic variable field (electrical intensity); parameters  $\beta$  characterize the gain of increasing of the damping force versus velocity;  $x_0$  – perturbation displacement [m];  $\delta$  – histeresys parameter. After the validation, with these mathematical models, the virtual LabVIEW instrumentation for the assisted numerical simulation and optimization of the dynamic results was created (Figs. 2...5).

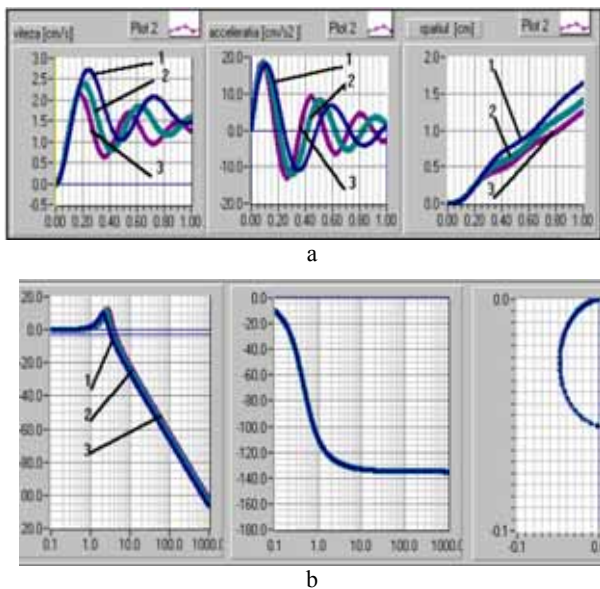


Fig. 2. Theoretical results after the numerical simulation of the LPM; a – indicial characteristics of velocity, acceleration and movement; b – frequency characteristics Bode and Nyquist.

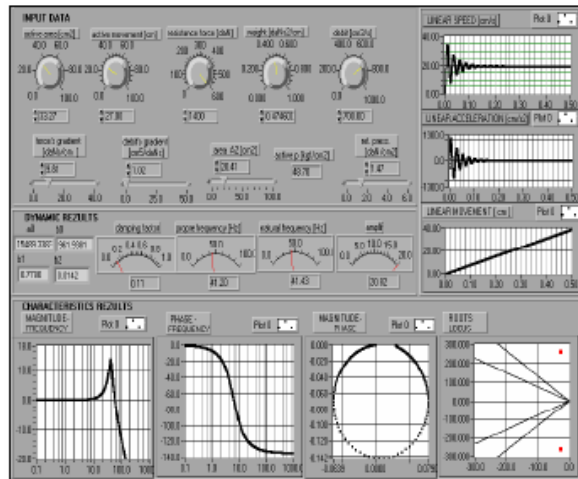


Fig. 3. The front panel of the LHM in the stage of the numerical simulation.

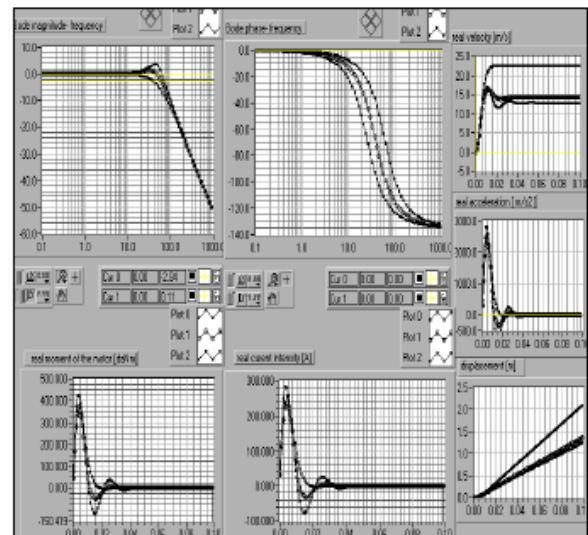


Fig. 4. The front panel and the results after the simulation of the electrical DC motor when was changes the rotor resistance  $R_a$  0.33, 0.5, and 0.8 ( $\Omega$ ).

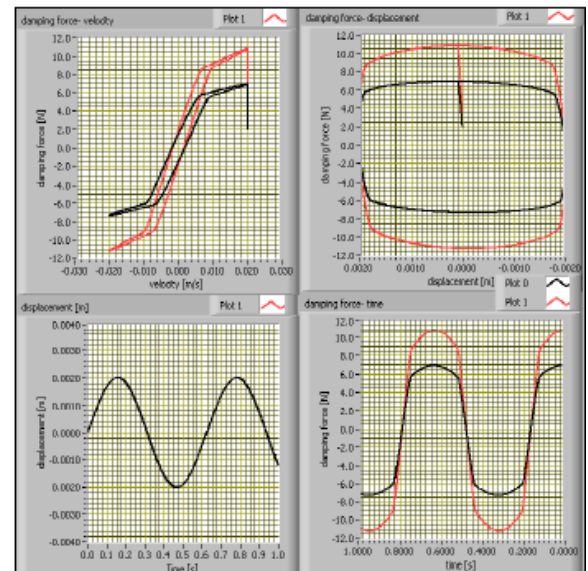


Fig. 5. The front panel and the results after numerical LabVIEW simulation of the magneto-rheological damper.

#### 4. VALIDATION OF THE MODELS

This stage of the research has contents the comparison of the theoretical results with the experimental and input in the model of some mathematical corrections.

The errors of the validation obtained for the LHM and the MRD by comparison of the real and simulate indicial characteristics, are near 1%, and shown in Figs. 6 and 7.

The errors of the validation appear because in a model isn't take in consideration the vibrations existing in a reality stand.

#### 5. ASSISTED OPTIMIZATION OF THE DYNAMIC BEHAVIOR

In this paper some ways to optimize the dynamic behavior of industrial robots were shown. All these researches were made using the validated mathematical models.

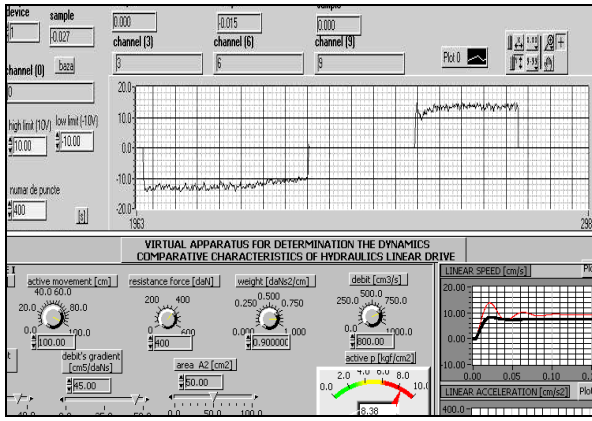


Fig. 6. Validation of the LHM.

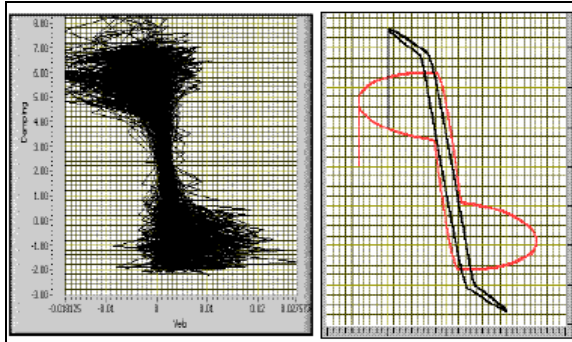


Fig. 7. Validation of the magneto-rheological damper.

5.1. Optimization of components with small frequency

In one servo system the component with the small frequency determines the small frequency of the system. For that it is very important to increase the frequency field by optimizing this component. Generally, this component is the drive and the load. The small frequency determines one bigger acceleration time, finally one bed promptitude. Simultaneously, it is necessary to obtain one good dynamic answer, that mince velocity of the output without vibration, with small time of response, without vibrations. In this example the loss flow between the rooms of the LHM was changed. The effect was the reduction of the vibrations, but a big value for the response time was obtained. To correct this time value, one PD<sub>2</sub> control law was applied (see Figs. 8 and 11).

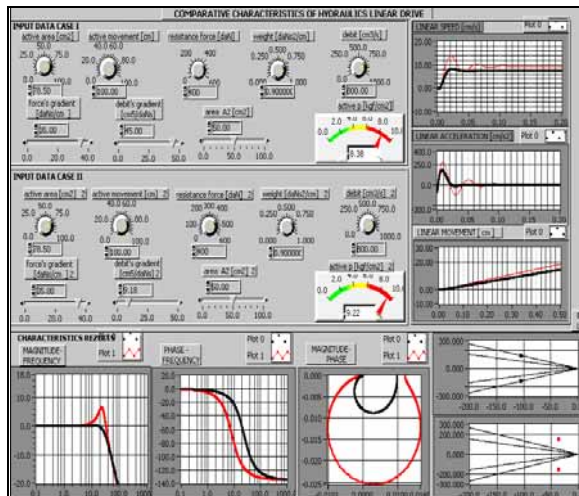


Fig. 8. The front panel of the VI-s to optimize the LHM; study case after changing the gradient loss between the two rooms  $a_m$  from 9.1cm<sup>5</sup>/daNs to 45cm<sup>5</sup>/daNs.

Table 1

The influence coefficients of the dynamic behavior

	$t_r$	$a_{max}$	$v_r$	$v_0$	
A	0.15	0.28 <b>1.86</b>	0.11 <b>0.73</b>	0.3 <b>2.0</b>	1.0 <b>6.66</b>
V	0.40	0.5 <b>1.25</b>	0.11 <b>0.275</b>	0.25 <b>0.625</b>	0.16 <b>0.4</b>
m	1.0	0.33 <b>0.33</b>	0.22 <b>0.22</b>	0.25 <b>0.25</b>	0.33 <b>0.33</b>

5.2. Choosing the optimal parameters with influences coefficients method

This method contents in the determination of some dynamic parameters after changing some constructive parameters of element or system, fig.2 and by reading of the rows and columns the big value of the influences coefficients calculated by relations:

$$C_i = \frac{R_{PCD}}{R_{PCF}}; R_{PCD} = \frac{PCD_i - PCD_f}{PCD_i}; R_{PCF} = \frac{PCF_i - PCF_f}{PCF_i} \quad (4)$$

where:  $PCD_i$  is the initial value of the dynamic behavior parameter;  $PCD_f$  – final value of the dynamic behavior parameter;  $PCF_i$  – initial value of the constructive-functional parameter;  $PCF_f$  – final value of the constructiv-functional parameter.

The mode whit each constructive or functional parameters were changed the dynamic behavior of the pneumatic motor have been made with the reading the bigger value of the influences coefficients in the each row, respectively in the each column of the Table 1.

Reading by rows the bigger values of the influences coefficients we observe: the increases of the active area  $A$ , determines with priority the increases of the critical frequency, the increases of the volume  $V$  determines with priority the increases of the answer time  $t_r$ , the increases of the mass  $m$  determines with priority the increases of the answer time  $t_r$  and the critical frequency  $\nu_c$  where is the most important dynamic parameter because influences the acceleration time in a velocity characteristic. By reading the bigger values of the influences coefficients for each column of the Table 1, we can observe that the all dynamic parameters are influenced by active aria  $A$ . With this method will be possible to see and to change on-line all constructive and functional parameters to obtain the optimal answer of the outputs. Training with these instruments assures one optimal means in the researcher's hands.

5.3. Input some additional parts in to the structure of the robot

In the case when isn't possible to obtain one good answer of the element or structure will be possible to input some additional mechanical or electrical parts to correct the behavior. In the paper it is show one case relation (5):

$$H_1(s) = \frac{x_2(s)}{x_1(s)} = \frac{b_2s^2 + b_1s + b_0}{a_4s^4 + a_3s^3 + a_2s^2 + a_1s + a_0}$$

$$b_2 = h_1h_2; b_1 = h_1k_3 + h_2k_1; b_0 = k_1k_3; a_4 = m_2m_3; a_3 = m_3h_2 + m_2h_1 + m_2h_2;$$

$$a_2 = h_1h_2 + k_1m_2 + k_2m_2 + k_3m_2 + k_3m_3 + k_4m_3; a_1 = h_1k_3 + h_1k_4 + h_2k_3 + h_2k_4 + h_2k_1$$

$$a_0 = k_1k_3 + k_1k_4 + k_2k_4 + k_3k_4 + k_3^2.$$

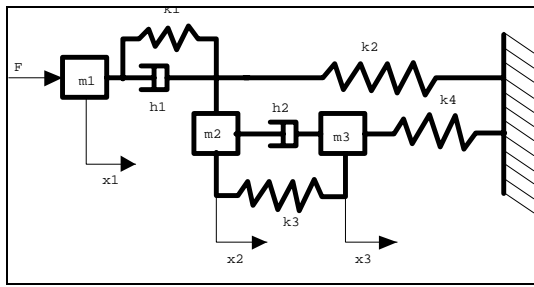


Fig. 9. Complex mechanical schema for correction of the dynamic behavior.

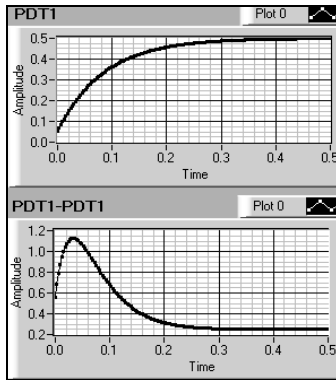


Fig. 10. Indicial characteristic of the output from the mechanical complex correction.

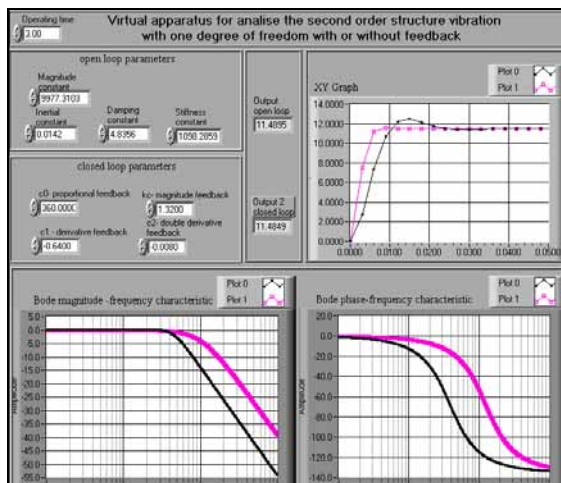


Fig. 11. The answer after the control PD<sub>2</sub> law applied to the LHM.

when it was introduced in the robot structure one complex mechanical correction system. With this correction and after choosing all parameters, it will be possible to obtain one good answer or correct them, Figs. 9 and 10.

**5.4. Choosing the optimal values of the correction and control laws**

After choosing the parameters of the element with small frequency, to obtain one good answer time, to adjust the magnitude of the output, it was necessary to apply the PD<sub>2</sub> control law. After application of this law the answer time is smaller and the magnitude of oscillation is canceled (see Fig. 11).

**5.5. Input some complex mechanical or electrical corrections and closed loops**

This method consists of one analysis of some closed complex systems schemas with many closed loops and

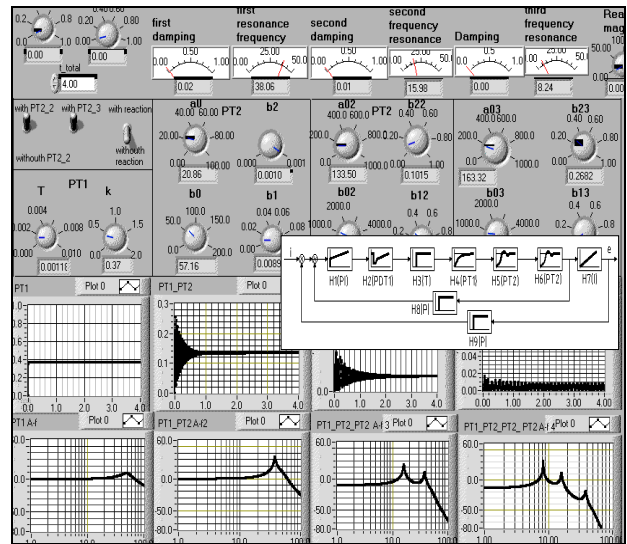


Fig. 12. The front panel of the VI-s for the simulation complex schemas with many closed loops, correction and regulator.

correction elements, by using the transfer functions and virtual LabVIEW proper instrumentation. This instrumentation assures easily the choice of the values of all parameters of components, for each of the closed loops magnitudes and for the corrections and regulators, Fig. 12.

**5.6. Choosing the frequency field and programming delay with Fourier analyzer**

The assisted research in the frequency field shows that the input delay of time into the movement determine the change of the Fourier spectrum. In this research one virtual LabVIEW instrument was used with the possibility of movement command and acquisition of the accelerations signal to construct the Fourier spectrum of the movement (see Fig.13).

**5.7. Using the intelligent dampers**

The intelligent damper system is the high tech of the dynamic research of the robot and content one complex schema with the sensors, signal conditioning modules, control soft and hard, amplifier of the electrical signal and actuator (the magneto-rheological damper), Fig. 14 and the results after application, Fig. 15.

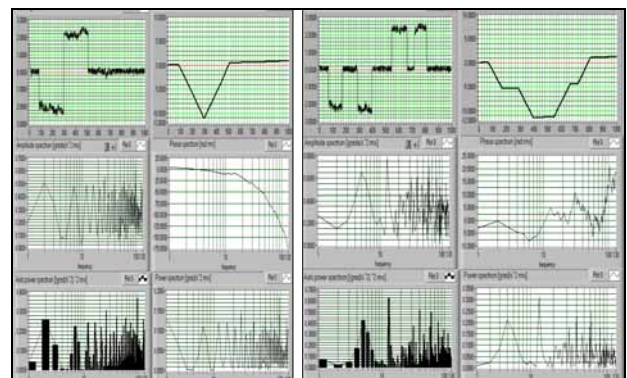


Fig. 13. Front panel of the VI-s with indicial characteristics of velocity and Fourier spectrum of the movement.

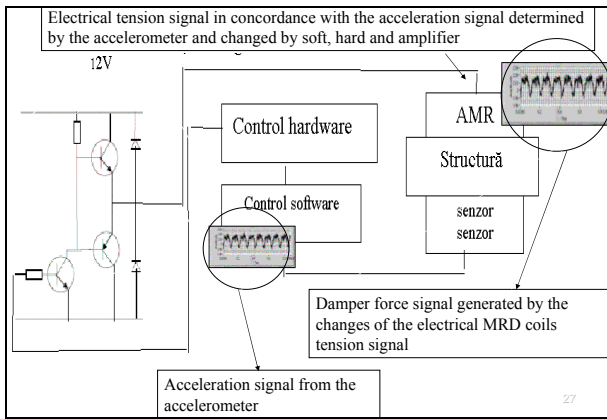


Fig. 14. Schema of the used intelligent damper system.

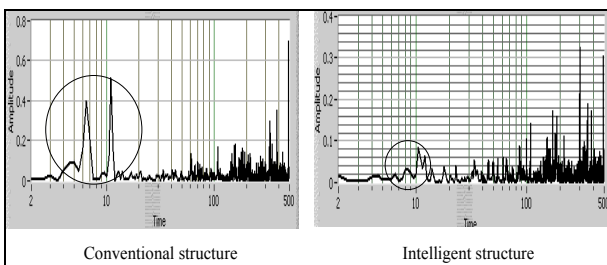


Fig. 15. Some results after application of the intelligent damper system to the robot structure.

## 6. CONCLUSIONS

The virtual instrumentation for the numerical simulation was created with the known mathematical model. The presented method assures the conditions to apply the smart components in the hydraulic or electric drive of the industrial robots (intelligent dampers). With the help of the influences coefficients method was possible to choose the optimal damper value of the rheological smart damper and all the optimal constructive and functional parameters. The assisted method with LabVIEW technique assures easily to show all influences of the constructive and functional parameters on the dynamic behavior. The virtual used instruments assure the comparative show between the real and frequency characteristics to understand the correspondent field of each characteristics and on-line influences. By using the virtual instrumentation exist the possibility to optimize the structure of the servo system, through impose the limits of the velocity, or introduce the constructive and functional changes or through changing the structure in one smart structure by introducing the closed loops or the different

control laws. The assisted experimental research with data acquisition offers the possibility to validate the mathematical model and to determine the real dynamic parameters and compare them with the theoretical results. The paper assures, for the researchers of this field, a real help and the physical virtual LabVIEW instruments that can be successfully used at the assisted dynamic behavior optimization.

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