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Dynamic Pressure Control in Reactive Sputtering Process

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Abstract: Reactive magnetron sputtering is used to create TiN_y and TiO_xN_y wear resistant nanostructure thin film coatings. In order to achieve a successful sputtering process which can be reproduced at any time, it is important to develop control units for the interdependent parameters of the system.

The purpose of this paper is to present the effect of the dynamic pressure upon the sputtering process and the design curs of the embedded pressure controller unit. The unit features a dual DSP microcontroller architecture in order to handle the defined tasks. There is a study on the analytical modeling process, which is based on the ideal gas law. With proper deduction and by introducing into the equation the gas flow rate and the pumping efficiency we managed to obtain a dynamic model. After conducting several tests we concluded that the obtained model has a global error less then 2%. The process is non-linear, but because throughout the sputtering process the value of the dynamic pressure varies in a relatively small and linear interval ($2.5 \cdot 10^{-3}$ and $3 \cdot 10^{-3}$ Torr), we managed to design, tune, fine-tune and implement a PID regulator. Based on simulation results we identified the need for a "*combined PID control algorithm*" which operates with different sets of parameters in function of the error, improving the quality of the control. In conclusion we can state that the developed embedded system fulfills all the requirements.

Keywords: reactive sputtering, thin film coatings, partial pressures, analytical model, embedded dynamic pressure controller, PID control algorithm.

1. Introduction

One of the most widely used physical vapor deposition (PVD) method for creating useful compound thin film coatings is the reactive sputtering [8]. At the International Physics Laboratory DC reactive magnetron sputtering is used to create titanium nitride (TiN_y) and titanium oxynitride (TiO_xN_y) wear resistant nanostructure thin film coatings with the use of argon inert gas, oxygen and nitrogen reactive gases and titanium target. These coatings are produced and studied with the aim to be used in different industrial applications exploiting their versatile properties.

It is important to emphasize that in order to perform a successful reactive sputtering process which can be reproduced at any time, due to the complexity of the process we need a controlled environment. This implies designing and implementing a series of control algorithms for the interdependent factors and parameters that influence the sputtering, such as the dynamic and partial pressures inside the vacuum chamber [1].

The purpose of this article is to present the process thru which we developed a controller for the dynamic pressure. This process includes the design of the hardware and software elements of the embedded system, the analytical modeling process with additional Matlab applications to tune and simulate the system and to verify the correctness of the non-linear mathematical model which played an essential role in designing, tuning and simulating the controller algorithm. The developed pressure controller unit due to the methodology and the Matlab applications can be used for other reactive sputtering systems as well with similar construction [1].

2. Concept of the dynamic pressure

In the sputtering process the argon inert gas has the role of bombarding the titanium metallic target without reacting with it. The oxygen and nitrogen gases on the other hand react with the sputtered material forming a stoichiometric compound. As an unwanted side effect oxygen or nitrogen coatings may be deposited on the surface of the target, process known as target poisoning. This phenomenon has a massive negative effect on the efficiency of the sputtering process and structure of the thin film coating. As a direct consequence the cathode gets electrically isolated, which means that it goes from metallic state to nitrated state [3] [5] [8]. In order to eliminate the presented side effect and to maintain the system in a desired operating point, it is necessary to design and develop a pressure controller unit.

Based on the simplified schematic (*Fig. 1.*) of the experimental equipment used at the International Physics Laboratory, it can be easily identified that the dynamic pressure is determined by the flow rate of the gases and the pumping speed of the turbomolecular pump. We can also state that the sum of the partial pressures produced by the inert and reactive gases introduced into the vacuum chamber is equal with the dynamic pressure [1] [5]. The pumping speed of the turbomolecular pump is constant, but it can be modified with the butterfly valve mounted directly in the evacuating duct. In order to perform a reactive sputtering process, inert and reactive gases need to be introduced into the vacuum chamber. This implies that these gases have to be introduced in a controlled way. For this task we used three independent mass flow controllers (MFC) with the help of which we can determine not only the desired flow rate, but we can measure it as well. These values are indispensable in the modeling process and they can be used also to verify if the MFC units are working properly.

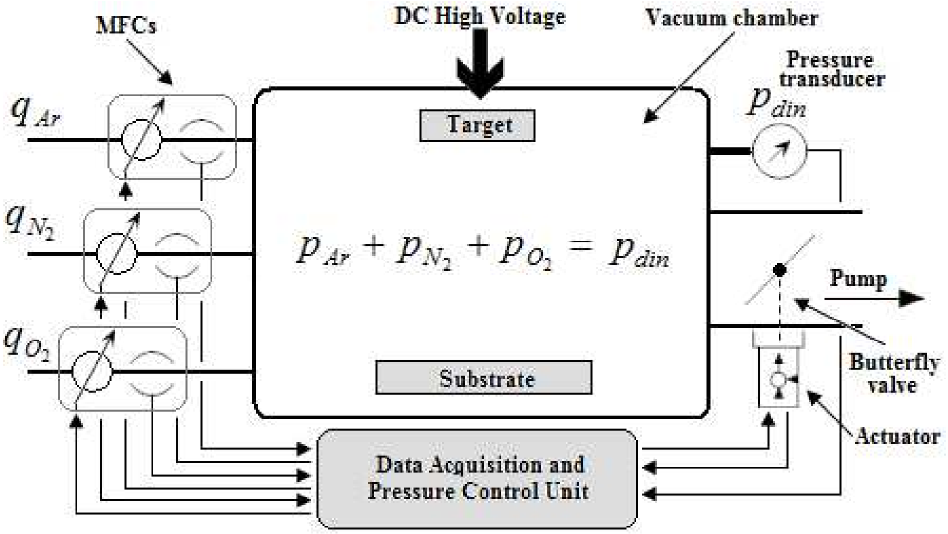

Figure 1: Simplified schematic of the experimental equipment [1].

3. Designing the embedded system

The first task was the development of an independent embedded system, also known as Data Acquisition and Pressure Control Unit. Based on the simplified schematic (*Fig. 1.*) we can identify the 5 measured analog inputs (the value of the dynamic pressure, the actual position of the butterfly valve and the three gas flow rate values) and 4 outputs (set point values for the mass flow controllers and for the actuator). All the inputs and some of the outputs are analog signals and because we are using numeric embedded system, we need to include analog to digital converters with different resolutions. For the flow controllers we are using 12bit MCP4921 digital to analog and integrated analog to digital converters.

When using two or more gases, we no longer can measure the values of the partial pressures, only the value of the dynamic pressure. For this task we opted for an analog Pfeiffer Vacuum capacitive transducer. The analog signal provided by the unit is digitalized with a 16bit external AD7705 sigma-delta analog to digital converter. We opted for this component, because it has good noise rejection, accuracy of ± 0.003%, low rms noise (< 600nV) and integrated self-calibration options, which eliminate endpoint errors. In order to achieve the desired pressure control accuracy, the converter functions only in the working interval of the pressure scale. The obtained resolution is $3.5 \cdot 10^{-7}$ Torr resolutions, which is adequate for our application.

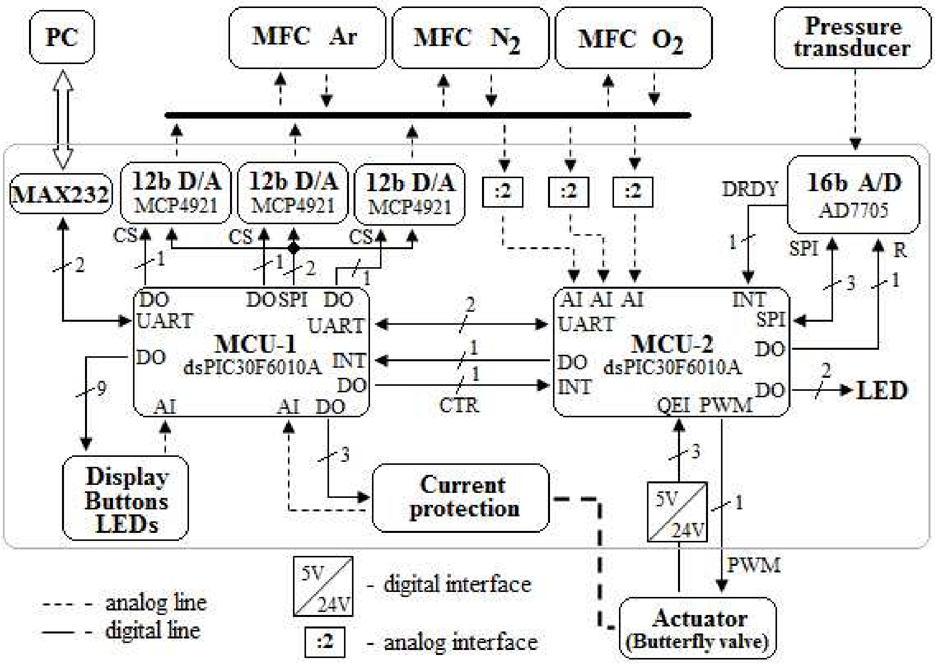

Figure 2: Bloc schematic of the embedded system.

The bloc schematic of the embedded system can be seen on *Fig. 2*. The Unit is based on two dsPIC30F6010A DSP microcontrollers with well defined functions and tasks. Because the computing capacity for all the tasks implemented (executing the control algorithm, operating the Human Machine Interface, data logging, communication, etc.) on the system exceeded the capacity of a single controller, we decided to divide the tasks between two DSPs, which exchange data via serial communication. The first unit controls the Human Machine Interface (the LCD display, the button cluster, LEDs and the potentiometer for manual control of the butterfly valve), generates the set point values for the MFCs and establishes communication with the second unit and the central computer. The second microcontroller is basically reserved for the pressure control task. From the pressure controllers point of view it is very advantageous that this unit directly measures all the gas flow rates, the dynamic pressure, the valve angle, runs the control algorithm (PID) and generates the control signal for the actuator.

The actuator assembly for the butterfly valve is based on a Futaba S3152 digital high speed and high torque RC servo unit and a Hengstler RI41 rotary encoder. A detailed study revealed that the unit has a maximum resolution of 0.15° and a global error less then 10%.

4. Modeling process - Methodology

One of the key features of this work is the analytical modeling process of the dynamic pressure. In order to simulate a control structure it is necessary to develop a dynamic model which is suitable for our experimental equipment. We obtained three separate dynamic models for the three gases, the sum of which is equal with the dynamic pressure [1] [4]. In the following we will present a generalized modeling process for one gas. The final equation is derived from the ideal gas law (1):

$$pV = nRT \tag{1}$$

From the ideal gas law we obtain a dynamic model by replacing the number of moles (n) with the ratio between the mass of the gas (m) and the molar mass (M) [1] [4]:

$$pV = \frac{m}{M}RT \quad \Rightarrow \quad \frac{dm}{dt} = \frac{MV}{RT} \cdot \frac{dp}{dt} \tag{2}$$

where:

$$\frac{dm}{dt} = q_{in} - q_{out} \tag{3}$$

The variation speed of the mass of the gas is equal with the difference between the introduced and evacuated gas flow rates (3). In this equation we have an unknown member, the value of the gas flow rate evacuated, because we do not have the possibility to measure it. This way it is assumed that q_{out} (4) is equal with the product of the pressure and the pumping efficiency which is a function of the valve angle alpha [1] [4].

$$q_{out} = p \cdot S(\alpha) \tag{4}$$

Based on butterfly valve geometry, the pumping efficiency has the following form:

$$S(\alpha) = K \cdot (S_1 + S_2 \cdot (1 - \cos(\alpha))) \tag{5}$$

Equation (5) can be simplified by merging the K constant with the two areas (S_1 and S_2) (6). This way the K_1 and K_2 constants can be identified based on real measurements.

$$S(\alpha) = K_1 + K_2 \cdot (1 - \cos(\alpha)) \tag{6}$$

In order to determine automatically the values of the constants, we developed different Matlab applications, which basically processed a series of measured values obtained with the help of the embedded system. The results showed that equation (6) isn't accurate enough. In order to rectify the problem, we observed that the K_2 is a linear function of the butterfly valve angle alpha [1]. We modified equation (6) and rerun the constant identifier application.

A. Result of the modeling process

As a result of the methodology presented in the previous chapter and with proper deduction we managed to obtain a non-linear analytical model for the three gases used (7).

$$\frac{dp}{dt} = \frac{RT}{MV} \cdot q_{in} - \frac{RT}{MV} \cdot p \cdot (K_1 + (a \cdot \alpha + b) \cdot (1 - \cos(\alpha))) \tag{7}$$

We conducted several test to verify the correctness of the principals, methodology and the obtained non-linear differential equation (7). The significant results are presented in *Fig. 3*. First we confirmed that the sum of the measured partial pressures (*Fig. 3a* argon – red dotted line, nitrogen – green dotted line, sum – red line) is equal with the measured dynamic pressure (*Fig. 3a* blue line) [1].

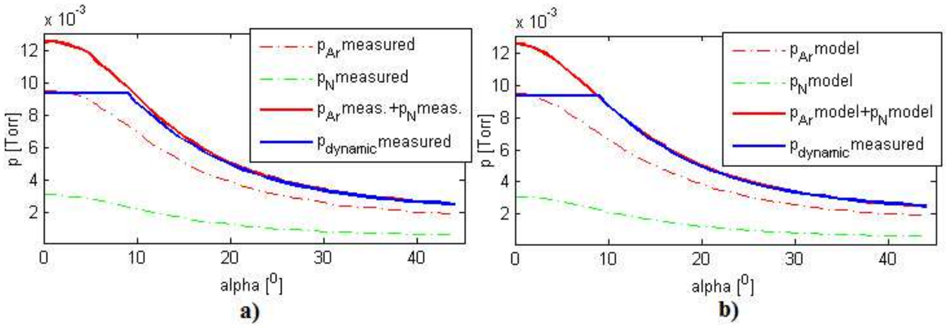

Figure 3: a) measured dynamic and partial pressures b) measured and simulated dynamic pressures and simulated partial pressures (argon and nitrogen) [1].

Because we can not measure pressure values greater then $9.5\cdot 10^{-3}$ Torr, on both figures we can see a saturation at this threshold. Taking into consideration that throughout the sputtering process the value of the dynamic pressure is between $2.5\cdot 10^{-3}$ and $3\cdot 10^{-3}$ Torr, the upper threshold mentioned before does not interfere with the control process.

After the second test we concluded that the sum of the simulated partial pressures (*Fig. 3 b*) argon – red dotted line, nitrogen – green dotted line, sum – red line) is equal with the measured dynamic pressure (*Fig. 3 b*) blue line). The global error between the measured and simulated dynamic pressure is less then 2% [1].

5. Control algorithm

The numeric embedded system presented in the first part of the paper features two DSP microcontrollers. In order to implement a PID control algorithm it is necessary to use a discrete form (9) instead of the continuous one (8) [6] [7].

$$H_{PID}(s) = \frac{U(s)}{\varepsilon(s)} = K_p \cdot \left(1 + \frac{1}{T_i \cdot s} + T_D \cdot s\right) \tag{8}$$

Starting from this equation with backward (9) method and with proper deduction we obtained the discrete form (10) of the PID control algorithm.

$$s = \frac{z-1}{T \cdot z} \tag{9}$$

$$H_{PID}\left(z^{-1}\right) = \frac{q_0 + q_1 z^{-1} + q_2 z^{-2}}{1 - z^{-1}} \tag{10}$$

where:

$$q_0 = K_p\left(1+\frac{T}{T_i}+\frac{T_D}{T}\right)$$
$$q_1 = -K_p\left(1+\frac{2T_D}{T}\right) \qquad (11)$$
$$q_2 = K_p\frac{T_D}{T}$$

From equation (10) we can obtain the discrete control signal, which has the following form:

$$u[k]=u[k-1]+q_0\cdot\varepsilon[k]+q_1\cdot\varepsilon[k-1]+q_2\cdot\varepsilon[k-2] \qquad (12)$$

The parameters present in the equation (11) need to be calculated only once or whenever the regulator parameters (K_p, T_i, T_d) are modified. The discrete control signal (12) is based on two basic operations and can be easily implemented on the microcontroller [6] [7]. To generate the T_s=*200 ms* sampling time we used a Timer and an interrupt routine.

As presented before the process is non-linear, but because throughout the sputtering process the value of the dynamic pressure varies in a relatively small interval ($2.5\cdot10^{-3}$ and $3\cdot10^{-3}$ Torr), we managed to found a set of regulator parameters with which the control algorithm functions well within the prescribed interval.

For tuning the Ziegler-Nichols method was used. At first we obtained a regulator which had unsatisfying results because the overshot and the response time at perturbation exceeded the maximum allowed values (*Fig.5* – blue line, *Table 1*). By increasing the proportional coefficient, at set value modification an overshoot appeared, but at perturbation both the overshoot and the response time were within the maximum allowed limits (*Fig. 5* – red line, *Table 1*). Based on these simulation results we identified the need of a "*combined PID control algorithm*" which merges the positive qualities of the two set of regulator parameters. The results are collected in *Table 1*.

The parameter switching mechanism can be seen of *Fig. 4*.

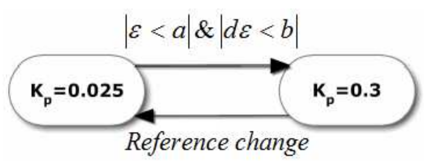

Figure 4: The parameter switching mechanism for the "*combined PID algorithm*".

By default the regulator uses the quick set of parameters. When there is a reference change (set value change) automatically the algorithm exchanges the two set of parameters. When the pressure stabilizes (the value of the error is less then "*a*" and the variation of the error is less then "*b*") then the mechanism changes back to the quick regulator. The values "*a*" and "*b*" were determined experimentally.

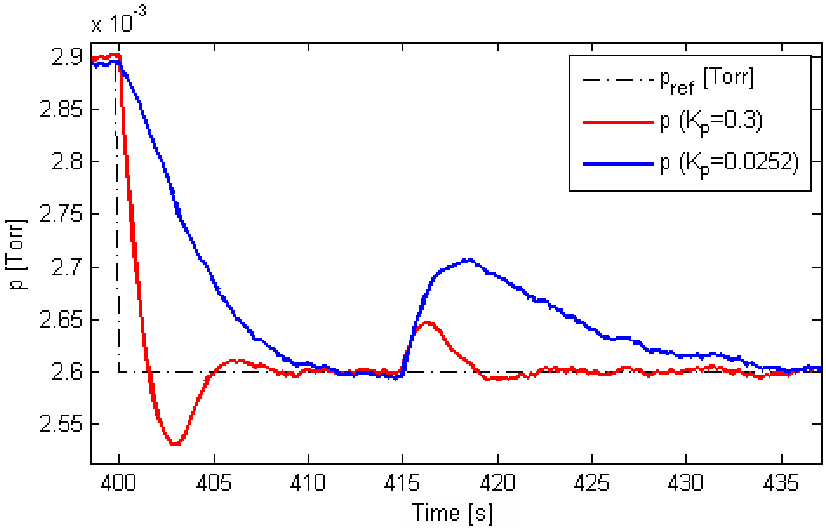

Figure 5: System response with PID control algorithm at set value modification and perturbation

Table 1: Simulation results for PID control algorithms

		Max. value	$K_p = 0.0252$	$K_p = 0.3$	*"Combined PID"*
Overshoot	σ [%]	3.46	-	2.65	-
Response time	t [s]	20	11.5	9	*11.5*
Overshoot and response time at perturbation	σ [%]	3.46	4.03	1.8	*1.8*
	t [s]	20	21.5	7	*7*

Based on the systems dynamic model we constructed a control loop (*Fig. 6*) in Simulink environment in order to tune the pressure control algorithm and to carry out the simulations presented before. Our main objective was to create a structure which functions as the real system, with a variation as little as possible. In order to achieve this, we conducted several tests and measurements on the experimental equipment and integrated the results into Simulink subroutines. We studied the characteristics of the mass flow controllers, the capacitive pressure transducers, the sputtering systems and based on this knowledge we introduced noises, saturations, different perturbations for pressure and flow rates.

During the sputtering process an unwanted phenomenon occurs which modifies significantly the structure of the deposited thin film. This phenomenon is the disruptions of the plasma. When this occurs, it is important to reignite the plasma in the shortest time possible. This can be achieved by increasing the dynamic pressure inside the vacuum chamber till the point where the plasma can reignite or by increasing the high voltage. We opted for the first solution. The "Control signals" (*Fig. 6*) subroutine contains a structure with the help of which we can simulate the interruption of the plasma and the reigniting procedure. This routine was created using real measurements and knowledge gained from different tests. When the plasma is disrupted, the algorithm automatically suspends the function of the pressure regulator and fully closes the butterfly valve in order increase the pressure. When the plasma reignites, the algorithm reopens the valve to his previous position and when the pressure decreases to its controlled value, the pressure controller is enabled. Based on these simulations we integrated this function into the embedded system as well.

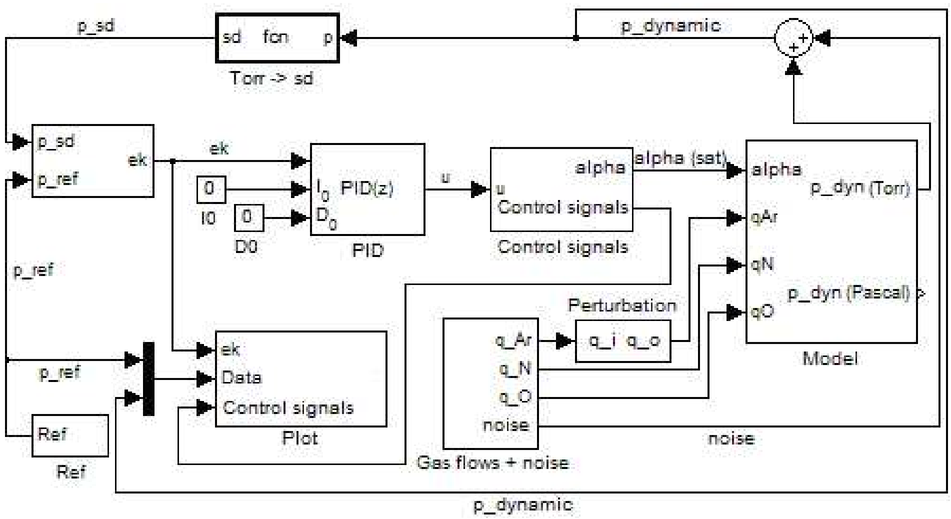

Figure 6: Control loop in Simulink environment.

After implementing the pressure controller and all the presented algorithms on the embedded system, we conducted tests to fine-tune the system and to verify the correct functioning. The benefits of using the "*combined PID control algorithm*" over the regular one are clearly shown on *Fig. 7*. There is no overshoot and the response time is shorter with four seconds.

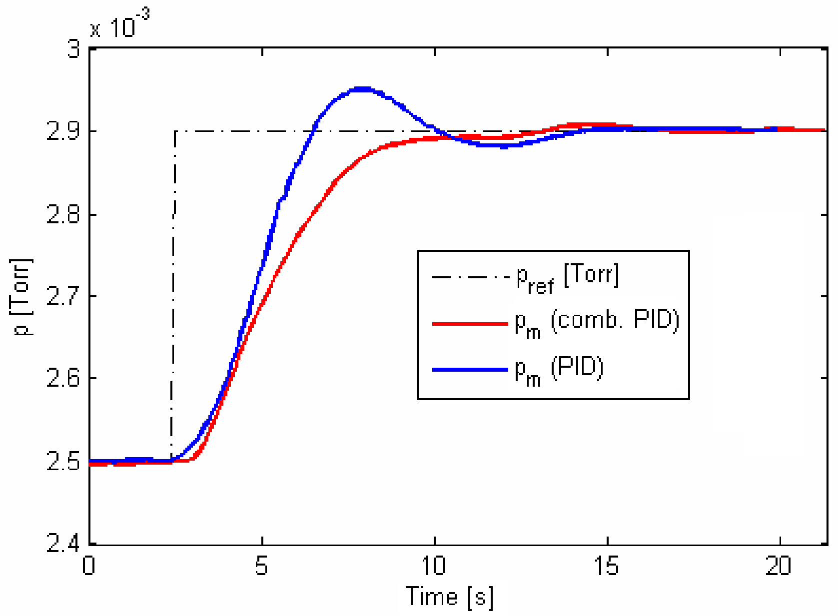

Figure 7: System response with implemented PID and "*combined PID*" control algorithms at set value modification – embedded system

6. Conclusion

As a result we managed to develop an embedded system for the control of the dynamic pressure. Throughout the study with proper deduction we obtained three analytical models of the partial pressures of the inert and reactive gases used in the sputtering process. It is important to emphasize that the modeling process is indispensable in designing, tuning and implementing the control algorithms. With the presented methodology and the developed Matlab applications the modeling process and the control unit can be used for other experimental equipments with similar structure. Based on simulation result we identified the need of a "*combined PID control algorithm*" which improved the control quality. In conclusion we can state that the developed system fulfills all the predefined requirements.

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