

## USING SOFTWARE APPLICATIONS TO SIMULATE THE OPERATIONAL PERFORMANCES OF A MANIPULATOR ARM

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**Abstract:** This study focuses on developing a virtual model of a manipulator arm, integrating both the mechanical structure and the complete driving system, comprising actuators and a power unit. The research aims to provide a general, adaptable mechanical configuration that can be used on various robot structures and has a wide range of applications. The integrated model allows for virtual simulation based on mathematical modeling and virtual instrumentation software.

**Keywords:** Virtual model, hydraulic system, manipulator arm, simulation, operational performance

### 1. Introduction

The manipulator arms, often programmable structures, consisting of multiple joints and links, represent the devices that perform a lot of tasks without direct physical contact. Thus, its structural elements allow it to move in a manner similar to a human arm and terminate with an end effector (e.g., a gripper or other specialized tool) to grasp, lift, and move objects in various industries for tasks such as manufacturing, surgery, and hazardous materials handling. Research from this paper focused on analyzing the dynamic behavior of a manipulator arm (used in emergency cases) using virtual simulation to effectively highlight its specific operational characteristics and dynamic.

As is generally known, the dynamic characteristics of manipulator arm revealed by simulation on virtual models (Figure 1) consist of:

- Torque and force analysis on each joint and link governing the manipulator arm's motion in different working scenarios for established structural integrity and design optimization.
- Vibration and stability analysis for arm's movement under various loads and at different speeds to investigate the arm response to dynamic forces, the natural frequencies, the impact overall stability, and reveal potential working cases with excessive vibration.
- Collision detection and avoidance for the optimization of fail-safe and damage-mitigation strategies.
- Payload and control parameter optimization to maximize efficiency and performance while minimizing wear and tear on the hydraulic system.

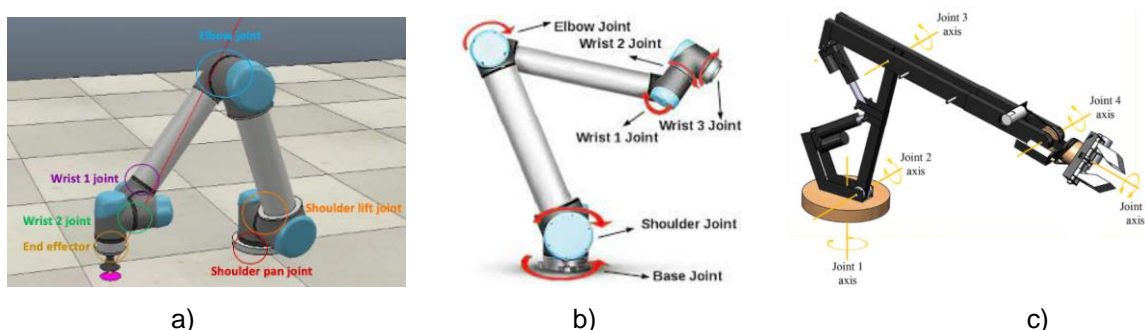


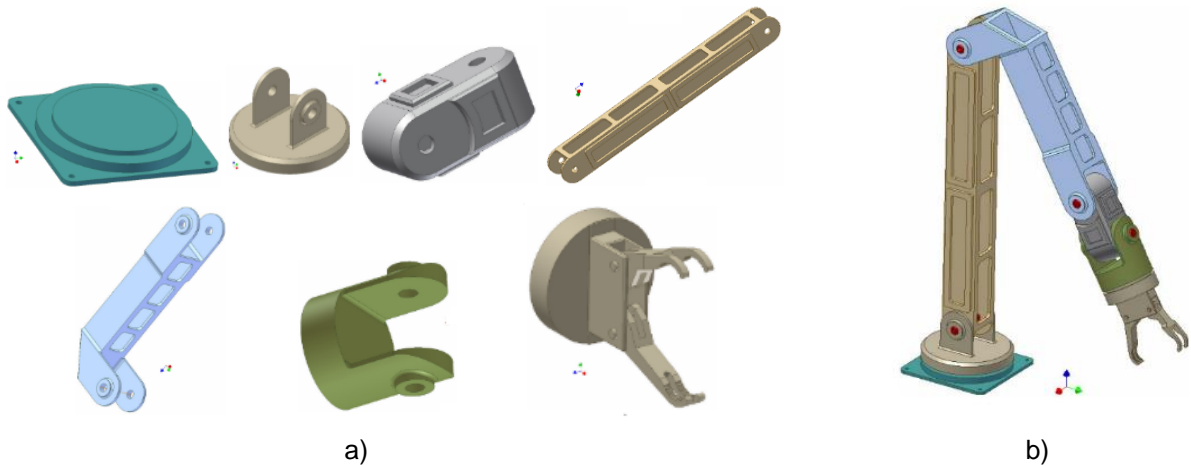
Fig. 1. Examples of robotic arms with multiple degrees of freedom [1,2,3]

### 2. Methods and Materials

Generally, for development of a virtual model of a manipulator arm are needed followings steps:

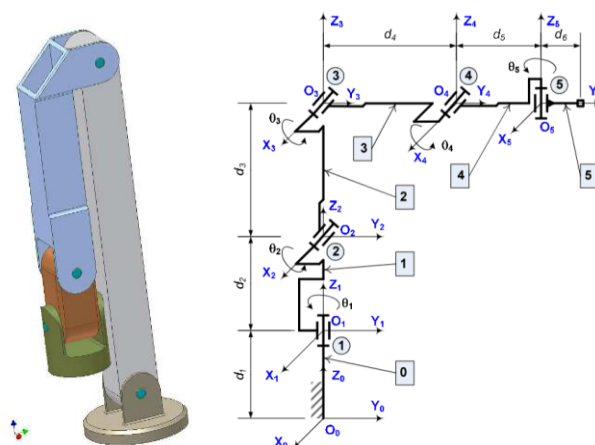
- designing and initial analysis.
- establishing physic-mathematic model of the mechanical structure.
- developing physic-mathematic model of the hydraulic drive system (hydraulic, electric etc.).
- modeling of the ensemble system.
- processing and analysis data.

The virtual modeling process for a manipulator arm begins with structural design using Computer-Aided Design (CAD) techniques [4,5]. This stage is foundational, creating a precise 3D digital representation of the arm's components before any physical prototyping or advanced analysis occurs. In Figure 2 All the main parts of the manipulator were designed using aluminum material (cod 6061 in Inventor Software libraries).



**Fig. 2.** Design of manipulator arm [6]:  
a) individual parts; b) assemble.

The position and orientation of a manipulator's end-effector are determined by its kinematics model (forward or inverse kinematics) useful to obtain a set of geometric transformations that describes the relationship between joint parameters and the end-effector's pose without considering forces, torques, or other dynamic factors (e.g., mass and inertia) [7]. In Figure 3 is described the specific configuration of the kinematic model of the manipulator arm's structure with 6 DOF showing the arrangement of its links and joints. The numerical symbols used have the next signification: (0) support; (1) rotational platform; (2) main arm; (3) handler; (4) coupler; (5) prehensile port-device.



**Fig. 3.** Kinematics model of the manipulator arm with 6 DOF (six rotations) [6]

The forward kinematics of the manipulator arm can be solved by Eq.(1) that describes the transformation matrix between the frame  $O_0$  and frame  $O_5$ .

$$T_5^0 = T_1^0 T_2^1 T_3^2 T_4^3 T_5^4 . \tag{1}$$

Therefore, the position and orientation transformation matrix between  $O_0$  and  $O_5$  can be determined using the Denavit–Hartenberg (D-H) parameter [8]. Knowing the workspace of a manipulator is a very important aspect and is represented by the total volume swept by the end effector as the manipulator executes all possible movements [9]. The applications or specialized tools (e.g., WSRender, Robotics System Toolbox – Matlab, Space Dream Robotic Arm, WorkSpace etc.) provide functions like robot kinematics and joint limits, collision detection, workspace generation, analysis and visualization of workspace data (Figure 4) useful for design engineers in their activities.

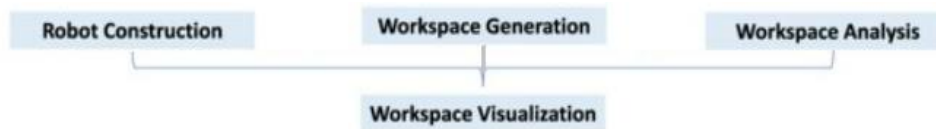


Fig. 4. Base configuration of the software architectures

For example, the linkage between the model performed in Autodesk - Inventor 9© and WorkSpace 5© was possible by exporting the Inventor part to a SAT file, which is a standard format for sharing 3D models between different CAD systems [10]. Once exported, the SAT file could be imported into WorkSpace 5©, creating a new, non-linked model in that program for working space generation of the manipulator arm (as can be seen in Figure 5).

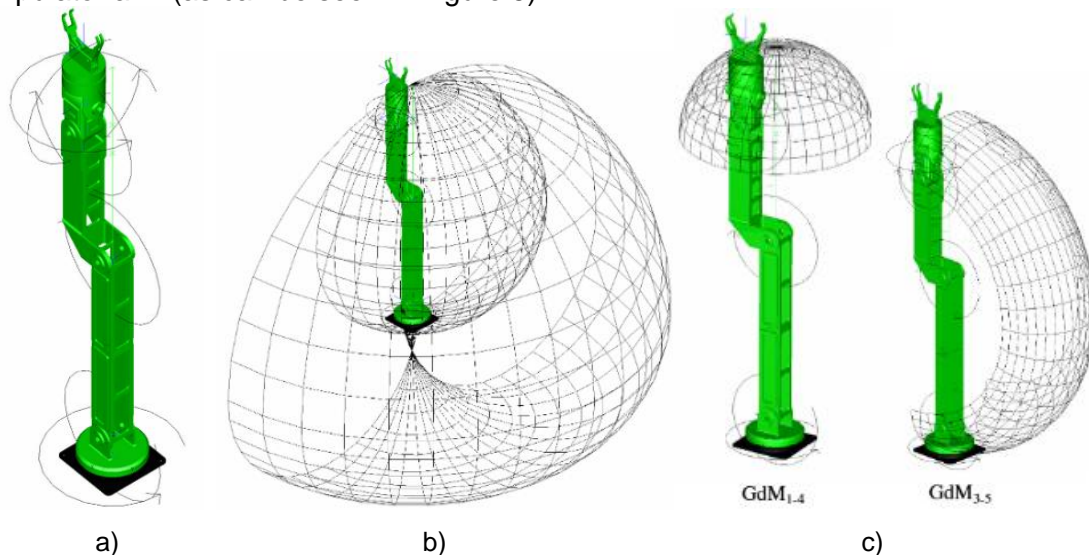


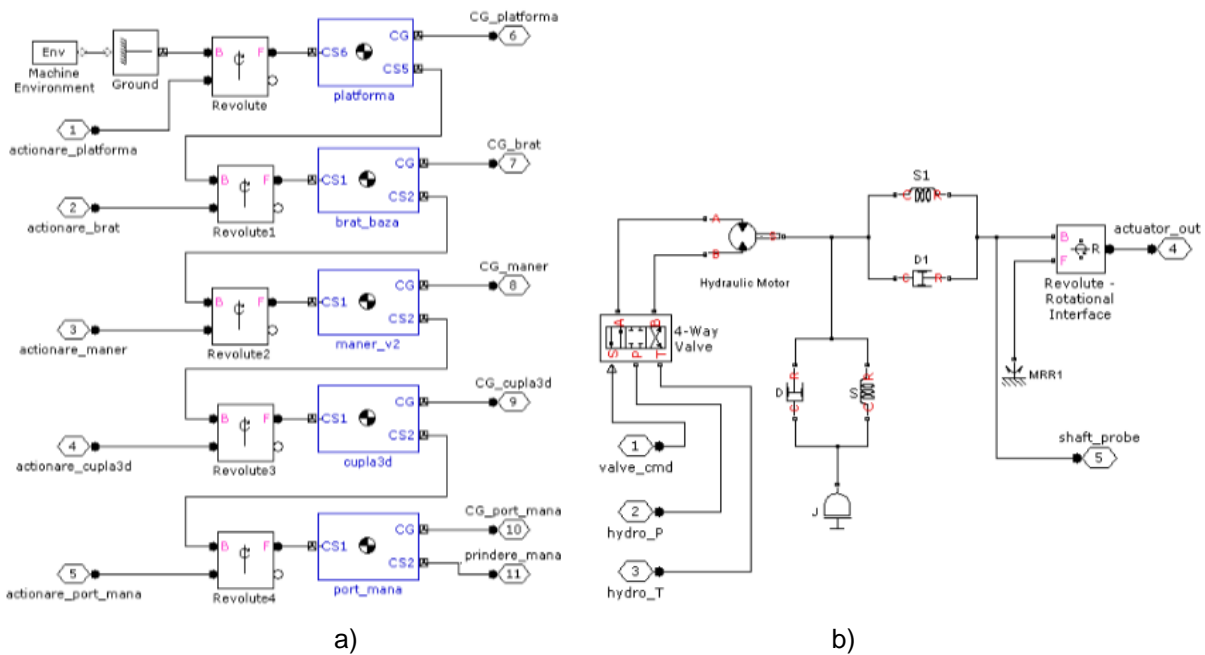
Fig. 5. Working space of the manipulator arm [6]:

a) SAT model; b) working space for the first three DOF; c) working spaces for other DOF (1-4, 3-5).

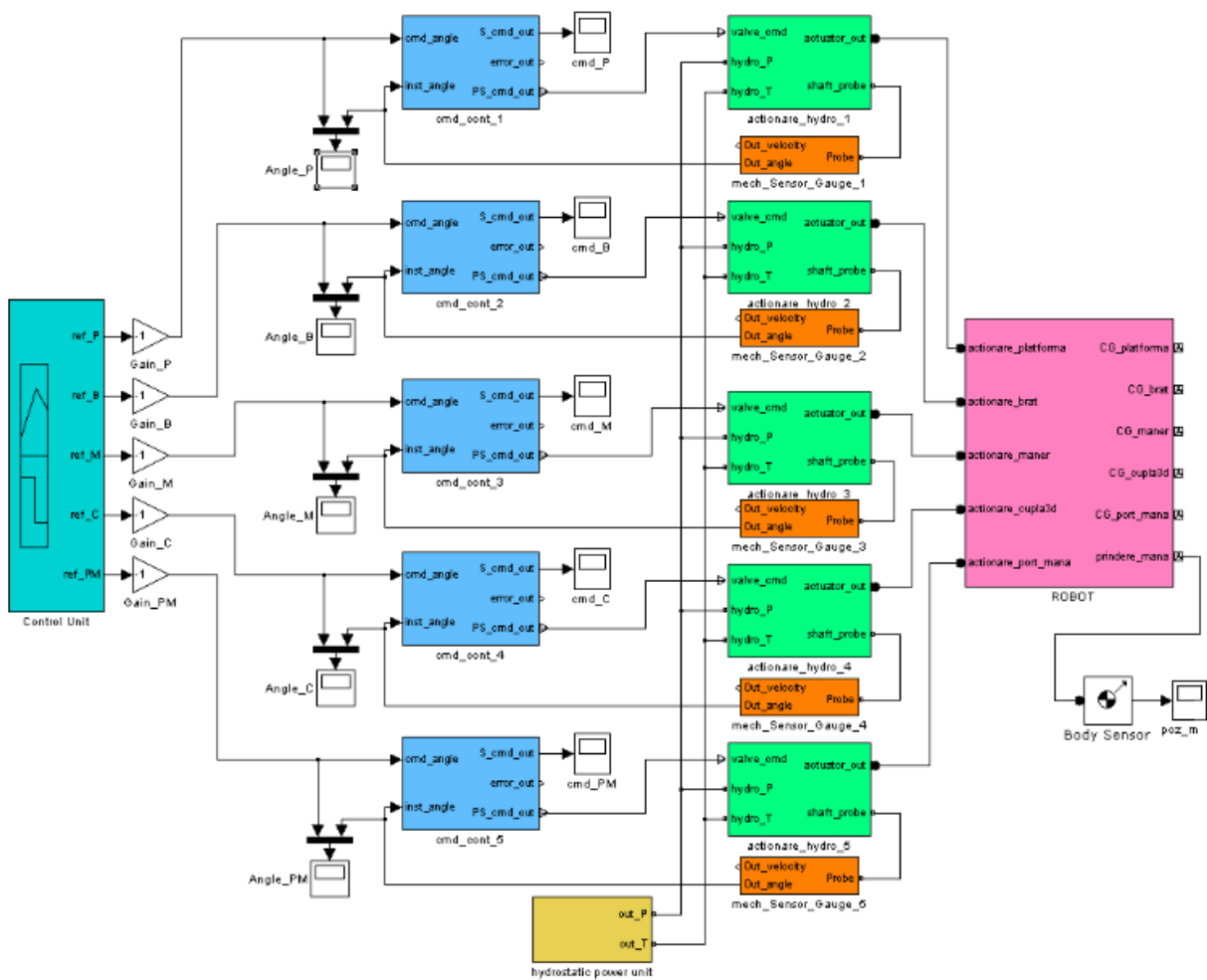
### 3. Simulation Results

The manipulator arm's mechanical configuration was developed using MATLAB's SimMechanics (Figure 6a) for direct angular input testing, while the hydraulic system, including the actuators and a classical power unit, was modeled in MATLAB's SimScape (Figure 6b). Finally, a complete diagram of a manipulator arm, including its power unit, was created using MATLAB and SimScape. Thus, the diagram, shown in Figure 7, illustrates the manipulator's components, while a specific part of the diagram, the power unit, uses a classical configuration developed through mathematical computations in the software.

The virtual manipulator arm model was tested in three steps: first, the mechanical structure was tested with direct angular inputs; second, the hydraulic driving system was tested both for individual actuators and then for the entire system working together; and third, the complete model was tested by having the hydraulic actuators directly drive the mechanical parts according to manual angular references.

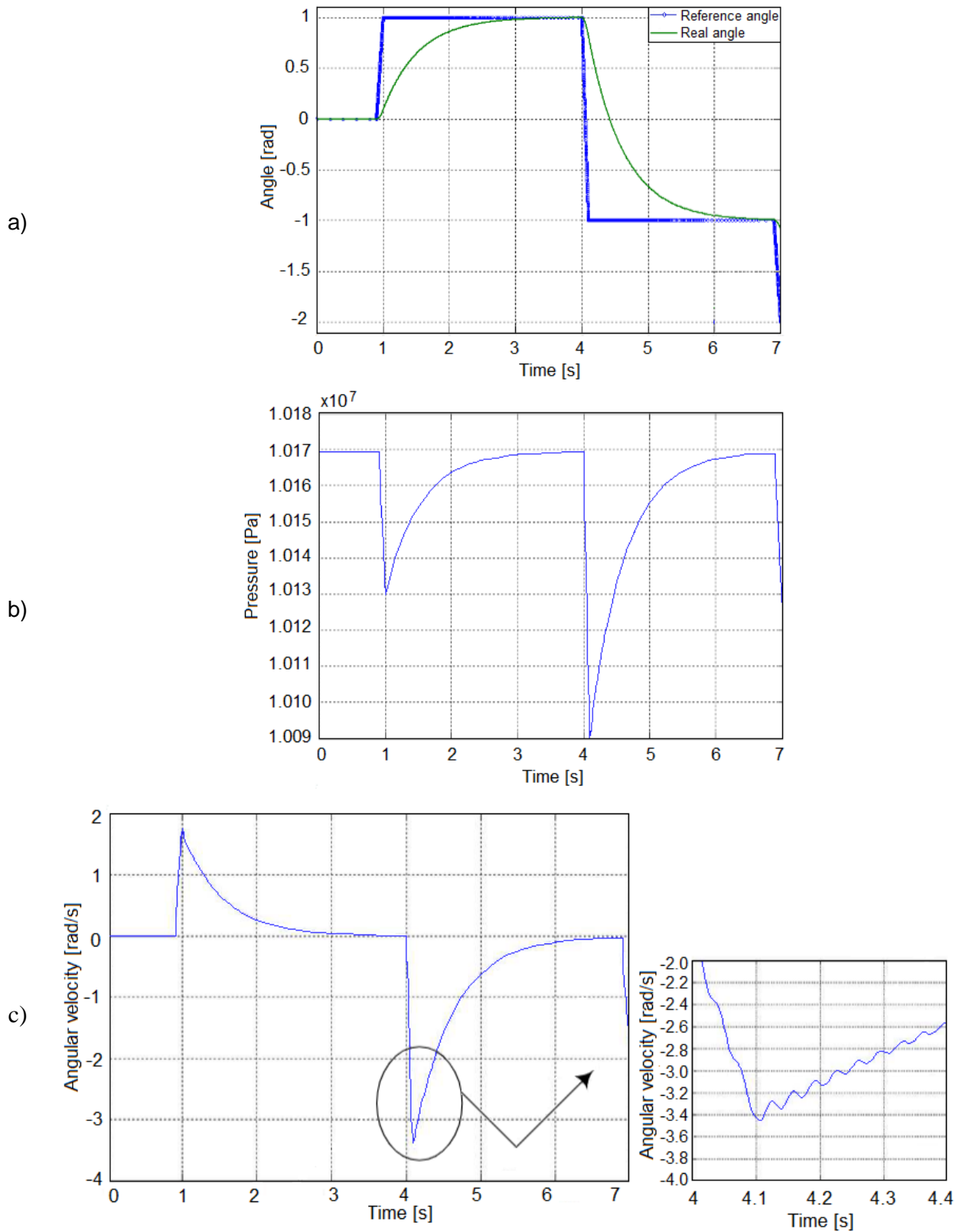


**Fig. 6.** Configuration of the virtual subsystems of the manipulator arm [11]:  
a) mechanical configuration in MATLAB - SimMechanics; b) hydraulic system in MATLAB - SimScope.



**Fig. 7.** General virtual model of the manipulator arm [11]

The results obtained from simulation process were depicted in Figure 8.



**Fig. 8.** The response of hydraulic system at input signal:  
a) angular displacement (thin line); b) total pressure in driving system;  
c) speed of the actuator shaft (with detail)

The results obtained in Figure 8 describe a simulation of a manipulator arm's motion, analyzing the resulting actuator displacement, system pressure, and shaft velocity. Thus, in Figure 8a two diagrams are represented to compare the desired reference movement (thick line) with the actual displacement of the actuator (thin line). The graph given in Figure 8b shows how the pressure changed within the system over the working cycle, based on the input requirements. The graph given in Figure 8c depicts the behavior of the velocity at the actuator shaft that demonstrates the dynamic effects on the system (consisting of rigidity and damping) with high-frequency oscillations caused by energy transferring back and forth between the system's kinetic energy and the elastic potential energy stored in its rigid components. As energy is dissipated, the magnitude of the oscillations in the velocity graph decreases. In the simulation, this effect is visible as the peaks of the velocity graph diminish over the duration of the movement. The ultimate effect is to bring the velocity to zero as the system settles into its final position.

#### 4. Conclusions

In this paper the design and behavior of working operation of a manipulator arm is discussed on an illustrative example based on serial arm with 6 DOF consisting in six rotations. The system has been simulated in MATLAB/Simulink environment, and it was determined that the desired control was achieved. The simulation shows how mechanical rigidity affects the oscillations in the velocity diagram and how damping influences the magnitude of these oscillations. It is important to note that the operational characteristics are not determined solely by kinematic conditions, but also by dynamic factors such as the overall system inertia. Overall, the performance of manipulator characteristics was put into evidence using dedicated application software available in the mechanical engineering field.

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