Research Article

An Interface Design for Comparison of Energy Consumption of Pneumatic and Ball Screw-Driven Linear Actuators

Batuhan ÖZÇAY[1a*], Serhat AZAR[1a], Elif ERZAN TOPÇU[2]

[1] Hid-Tek Ltd. Şti.,Ar-Ge Merkezi, 16110, Bursa
[a] Bursa Uludağ University,
Graduate School of Natural and Applied Sciences, Department of Mechanical Engineering,
16059, Bursa, Türkiye,
Orcid ID:https://orcid.org/0009-0001-3895-3208
Orcid ID:https://orcid.org/0009-0007-1011-5564
E-mail: 502210034@ogr.uludag.com.tr / tasarim4@hid-tek.com.tr
[2] Bursa Uludag University, Faculty of Engineering, Department of Mechanical Engineering, 16059, Bursa, Türkiye, Orcid ID: https://orcid.org/0000-0002-6115-3110, E-mail: erzan@uludag.edu.tr
[*] Correspondence: tasarim4@hid-tek.com.tr

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Abstract

Today, engineers use many computer programs and applications to model and analyze engineering problems. However, the demand for user-friendly interfaces and web-based applications is increasing daily to select the appropriate system components according to different working conditions and to evaluate the results comparatively. Also, most of these interfaces calculate the actuators' size and are mostly developed by foreign manufacturers. Nowadays, with the increase in energy costs, the demand for the use of energy-saving products is also increasing. Therefore, examining and comparing the energy consumption of the actuator elements used in the systems depending on the work done is necessary.

In this study, the authors discussed the issue of developing an interface that can define the appropriate size of actuators for the different operating conditions, such as different loads, slopes, friction, opposite load, and speed, and enable comparative energy consumption according to these elements for electro-pneumatic and servo motor driven ball screw shaft driven actuator types.

Keywords: Energy consumption, electro-pneumatic actuator, ball screw driven actuator, user interface design

1. Introduction

Today, engineers use computer-aided methods to solve most engineering problems. These computer-aided programs are preferred in engineering systems' design, modeling, and analysis studies. In the infrastructure of engineering programs, equations of motion that represent the dynamic behavior of the examined system according to the situation of the problem are used. Codes written in basic programming languages such as C/C++ and Python or engineering calculation programs such as MATLAB, ANSYS, Simcenter AmeSim ext. are widely used in solving engineering problems. However, to create solutions using these programming languages, it may be necessary to master these languages/programs and spend more time. For this reason, the demands for working with graphical user interfaces (GUI) or web-based applications are increasing daily for users whose primary purpose is to dimension and select machine elements for specific operating conditions.

The infrastructure of these programs also includes analyses of the design and mathematical models of the relevant engineering system. It is seen that these interfaces are mostly made available by companies that produce the relevant actuator or system component and are mostly used for product selection. GUI tools are widely used in education and industrial areas because they provide a visual and user-friendly approach. Aliane (2010) presented an interactive module using MATLAB-Simulink and MATLAB-GUI tools for learning the fundamental and practical issues of servo systems to contribute to lectures in control engineering and robotics [1]. Tao et al. (2021) developed a GUI tool in MATLAB, a teaching application for undergraduate engineering students to model a ferroresonance circuit. So, students can adjust the system parameters in this tool to test various types of resonance voltage waveforms to obtain the corresponding power frequencies directly using GUI [2]. GUI tools have more importance for distance learning, so developing tools for this type of education has been used for years. Casini et al. (2003) presented a remote laboratory of automatic control using GUI to allow students to interact with physical processes easily through the Internet. The student can run experiments, change control parameters, and analyze the results remotely [3]. Şefkat (2010) conducted a computer simulator program and GUI structure, providing a visual approach for designing and analyzing an electromagnetic system with MATLAB-Simulink [4]. Khaisongkram et al. developed a CAD tool for multi-objective controller design based on the MATLAB program and constructed a basic GUI to provide a visual approach to specifying the constraints [5].

In industrial applications, motion transmission is carried out with fluid power systems (pneumatic, hydraulic) or electromechanical actuators. In electromechanical systems, linear motion occurs with ball screw-shaft, roller screw shafts, belt-pulley, and chain components driven by electric motors or linear motors directly. These systems are used for many purposes, such as product transportation, placement, and pressing in various industrial areas such as aviation, defense, shipbuilding, and healthcare. Therefore, the products to be used in these areas must be designed and selected according to the work conditions. Nowadays, with the awareness of energy costs and their impact on the environment, users and manufacturers are increasing the demand for less raw material usage and energy-saving products.

İnci and Erzan Topçu (2023) conducted a comparative cost analysis between a pneumatic long-stroke actuator and a toothed belt-driven electromechanical actuator, along with an examination of the break-even point. The study observed that initial investment costs are higher for electromechanical systems, but over the years, the cost of pneumatic systems has increased due to annual consumption costs [6]. Li et al. (2009) proposed a simplified method to minimize the mechatronic system's energy dissipation, so they investigated to determine an optimal lead of the ball screw-nut system. They showed that dissipated energy depends on forward and backward efficiencies, which are the lead's functions and the system's viscous friction. Simulation results defined that the proposed optimal lead can decrease the dissipated energy by 50% compared to a conventional inertia matching method [7]. Mohammad et al. (2014) examined the sliding mode control approach on a ball screw using a linear guidance system to reduce the electrical energy consumption of the ball screw system. Experimentally, they have shown that this control method significantly reduces electrical energy consumption [8]. Caracciolo and Richiedei (2014) conducted a study on ball-screw mechanisms. They examined the ball-screw's critical speed, service life, and buckling load, highlighting the importance of mechatronic considerations. The study also evaluated the controlled system performances through the inertia ratio and selected the most suitable ball-screw system [9]. Liu et al. (2020) investigated the dynamic behaviors of industrial tools equipped with ball-screw systems and modeled the interactions of system components using bond graph theory to understand and model the relationship between dynamic behaviors and energy consumption. Their study revealed how machinery equipment utilizing ball-screw systems behaves under different operating conditions and explained the impact of this behavior on energy consumption [10]. Rigacci et al. (2020) investigated a ball-screw mechanism system's mechanical behaviors and electrical power consumption experimentally. Through their experiments, they examined the energy consumption of the system based on the ball-screw nut type, presenting results on how system parameters should be adjusted for optimal performance [11]. Harris et al. (2014) investigated comparatively the minimisation of air consumption in pneumatic actuators using different approaches. To simplify the implementation of energy-saving circuits for industrial end-users, a software program has been developed based on a combination of genetic algorithms and dynamic simulations [12]. Blagojevic et al. (2020) examined the differences in energy consumption across various diameters of pneumatic actuators in combination with compressed air at different pressure levels [13]. Raisch and Sawodny (2020) conducted modeling and analysis on a pneumatic actuator cushioning system focusing on energy savings. The study considers the energy savings on the pneumatic actuator and examines the impact of energy-saving components on the overall system performance [14].

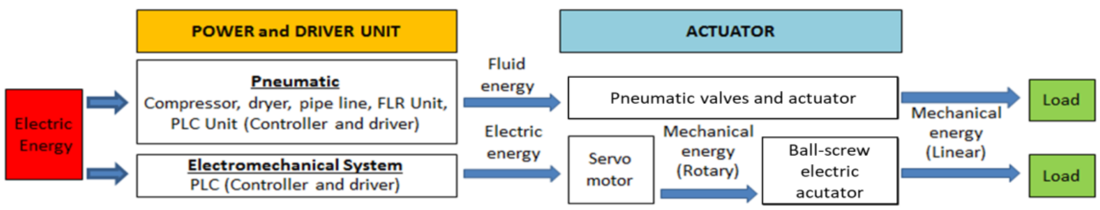
According to our research, a nationally produced GUI program that can make actuator selections according to the working conditions entered by the user has yet to be identified. So, there was a need to develop a user-friendly interface for sizing and selecting the actuator element for both electromechanical and pneumatic actuators. With this study we will carry out in this context, we want to take the actuator selection one step further. This study aims to provide comparative content regarding the sizing, selection, and energy consumption of electromechanical and pneumatic actuators by the user's operating conditions. In this study, the development of an interface that simultaneously compares the energy consumption costs of an electro-pneumatic actuator with the energy consumption costs of servo motor-driven ball-screw shaft actuators was examined. The issue of developing an interface that can select the appropriate actuator for the application and comparatively calculate the energy consumption depending on the mass, slope, friction values, and working speed according to the pressing or carrying process determined by the user is discussed. It is planned to create an infrastructure to make this interface work web-based in future studies.

2. Materials and Methods

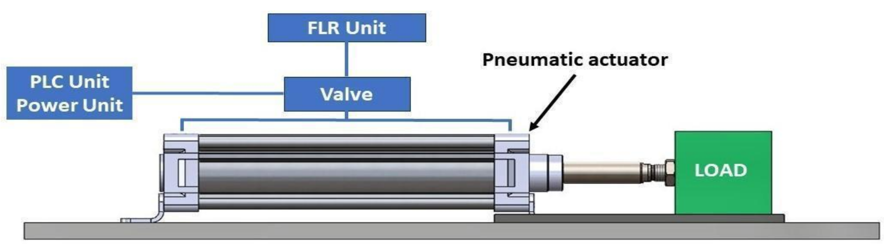
This section briefly explains the actuator types examined comparatively in the study and presents the method applied.

2.1. Pneumatic actuators

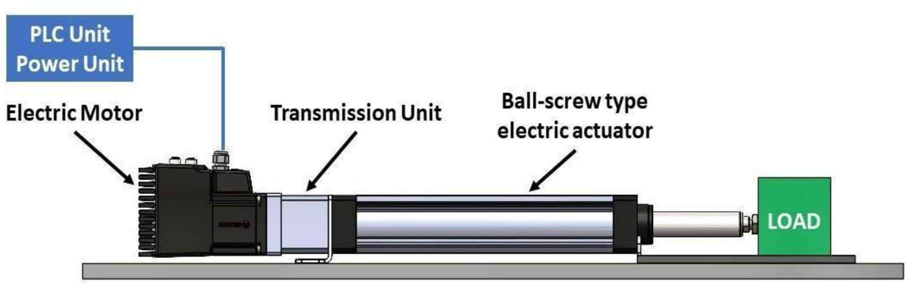
Compressed air units are often used in factories to serve different purposes. It is distributed into the factory through pipelines. As shown in Figure 1a, to provide power transmission to the actuator, electrical energy is transferred to the valve unit after passing through the compressor, dryer, distribution line, and conditioner units. In this study, considering that compressed air production systems are located in factories, the costs of this part were excluded from the analysis. The control unit and drivers used to determine the direction of movement of the pneumatic actuators are used to control the valves and, if any, to transmit the signals from the feedback unit to the control unit and to perform closed-loop control 1. Figure 1b shows the schematic of the electro-pneumatic valve actuator system examined in the study.



a) Flow of energy for two types of actuators



b) Electro-pneumatic actuator system



c) Servo motor driven ball-screw electric actuator system

Figure 1: Pneumatic and Electromechanical System Elements and Flow of Energy

2.2. Electromechanical Actuators

Obtaining linear motion by using electrical energy from electromechanical actuators is achieved either by linear motors or by driving linear motion mechanisms with electric motors. In electric motor-driven systems, linear motion is achieved by transferring the motion directly to the ball screw shaft and planetary roller screw mechanisms via coupling or transmission organs such as gearboxes and belt pulley mechanisms. This technology, which can be considered relatively new to pneumatic and hydraulic actuators, finds use in offices, homes, and industrial users. These systems produce mechanical work according to the movement and working conditions determined by the user. This study investigates a ball-screw mechanism driven by a servo motor, as shown in Figure 1c.

2.3. Basic equations of the system and flowchart for the user interface tool

Figure 2 shows the schematic view of the actuator system considered in the interface design phase for both types of actuators. In the analysis, two different processes can be selected: load carrying and pressing. Friction and slope at the desired angle were also considered. Basic equations to develop the user interface for both actuators are given below.

The annual air consumption cost of the pneumatic system can be calculated using the following steps, considering the air consumption amount. Annual air consumption amount of a pneumatic cylinder without leaks;

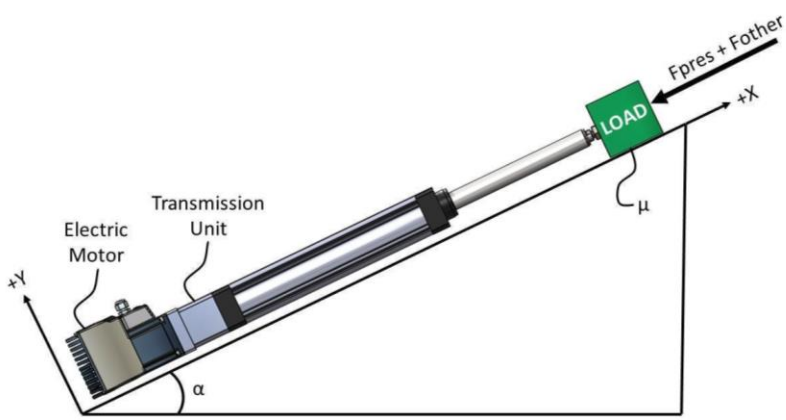


Figure 2: The investigated actuator system scheme

$$H_{ca} = \left(\frac{P_{supply} + P_{atm}}{P_{atm}}\right).\left((A_{forward} + A_{backward}).L_{cyl}\right).(n.n_{year}.n_{day}.60) \quad (1)$$

Based on this, the annual energy cost of the system is calculated with Equation (2).

$$Energy\ consumption\ per\ year = H_{ca} * H_{pe} \quad (2)$$

Air production energy per unit volume was taken as 0.12 kWh/m3 and electrical energy cost was taken as 0.13€/kWh [15,16]. Accordingly, the annual energy cost can be calculated as below;

$$Energy\ cost\ per\ year = Energy\ consumption\ per\ year * Electricity\ energy\ cost$$

Kinematic variables of the actuators are defined as Equation (3,4)

$$x = \int v dt \tag{3}$$

$$a = \frac{dv}{dt} \tag{4}$$

According to Newton's II. law of motion, the axial force to move the load can be calculated using Equation (5) by considering the slope, friction, and mass;

$$F_{axial} = m_{load}.a + F_{friction} + F_{ext} \tag{5}$$

Buckling is an important phenomenon so it must be checked regardless of the type of actuators, such as pneumatic or electromechanical. Buckling can be calculated using Equation (6)

$$P = \frac{k.\pi^2.N.E.I}{L^2} \tag{6}$$

The critical speed of the ball-screw electric actuator can be defined as below;

$$n_{crt} = f.\frac{d_r}{L_{cr}}.10^7 \tag{7}$$

The equivalent dynamic axial force during the motion is defined as Equation (8)

$$F_{mean} = \sqrt[3]{\left|F_{eff1}\right|^3.\frac{|n_1|}{n_m}.\frac{q_{t1}}{100\ \%} + \left|F_{eff2}\right|^3.\frac{|n_2|}{n_m}.\frac{q_{t2}}{100\ \%} + \cdots + \left|F_{effn}\right|^3.\frac{|n_n|}{n_m}.\frac{q_{tn}}{100\ \%}} \tag{8}$$

The average speed;

$$n_m = \frac{|n_1|.q_{t1} + |n_2|.q_{t2} + \cdots + |n_n|.q_{tn}}{100\ \%} \tag{9}$$

Nominal service life in revolutions;

$$L_s = \frac{f_{ac}.C_a}{F_{mean}}.10^6 \tag{10}$$

Static load rating ;

$$C_0 = F_{max}.f_s \tag{11}$$

The torque of the system can be defined generally as

$$T = \frac{F_a . l}{2\pi . \eta} \tag{12}$$

The rms torque of the

$$T_{rms} = \sqrt{\frac{T_1^2 . t_1 + T_2^2 . t_2 + \cdots + T_n^2 . t_n}{t_1 + t_2 + \cdots + t_n}} \tag{13}$$

To determine the annual energy cost of the servo motor-driven ball screw electric actuator system, the energy consumption in the total cycle time must be calculated. In automation systems, the dynamic behavior profile of the load is determined depending on the number of cycles and speed. The motor torque can be calculated as below by considering the system's load, friction, and inertia moments according to Newton's II. law of motion,

$$\sum T_{net} = J . \frac{dw}{dt} \tag{14}$$

The output power of the motor and energy equation can be defined as below;

$$P_m = T_m . \omega_m \qquad E_m = \int P_m dt \tag{15}$$

According to this efficiency of the system;

$$\eta = \frac{\int P_{mec} dt}{\int P_{elc} dt} = \frac{E_{mec}}{E_{elc}} = \frac{E_{forward} + E_{backward}}{Eelc} = \frac{2.(E_{acceleration} + E_{constant\ speed} + E_{deceleration})}{Eelc} \tag{16}$$

The Excel program was used at this stage of the study for the developed interface. After this phase of the study is completed, a web-based graphical user interface will be done. The flow chart of the user interface is shown in Figure 3.

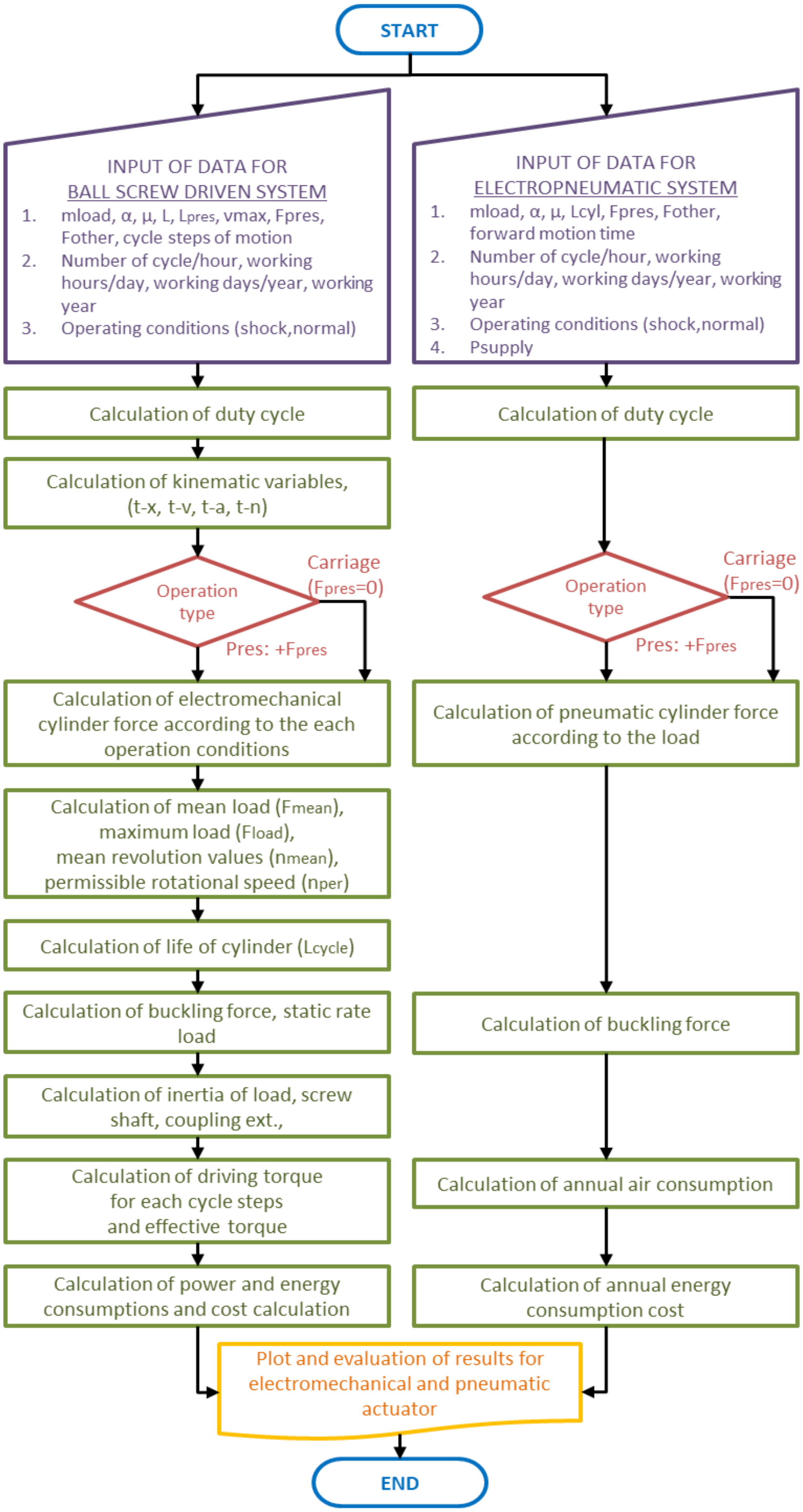


Figure 3. Flow chart of the graphical user interface

3. Case study for carrying application

The results obtained from the case study for the WLA4-063 model electromechanical actuator are presented below. The ball screw diameter of the actuator is 25 mm, and its pitch is 10 mm. Other information about the product is that the tooth root diameter is 21.6 mm, C_{stat} is 24,600 N, and C_{dyn} is 16,140 N. For the pneumatic actuator, the product coded WAC-080 with a piston diameter of 80 mm was chosen as an application example. This study does not include maintenance for the pneumatic actuator and first investment costs, and inertia moments of ball-screw, electric motor are ignored. No-load moment and efficiency of electric motor are taken as 0,35 Nm and 0,90 respectively. Table 1 shows the input values for GUI. As can be shown from the table, the entrance of the values such as working conditions, the slope of the system, the mass of load, the friction coefficient of the load with the surface, and the stroke of the cylinder is enough to calculate all outputs shown in Table 2.

Table 1: Input variables for GUI

m_{load}	250 kg	$t_{forward}$; t_{acc}; t_{dec}; t_{delay}	3s; 1s; 1s; 1s
α	0°	n_h	514 cycles
μ	0,5	n_{hd}	20 hours
L_{cyl}	0,25 m	n_{dy}	250 days
Operation condition	Normal	n_y	5 years

Table 2: Outputs calculated from GUI

a) Electromechanical actuator

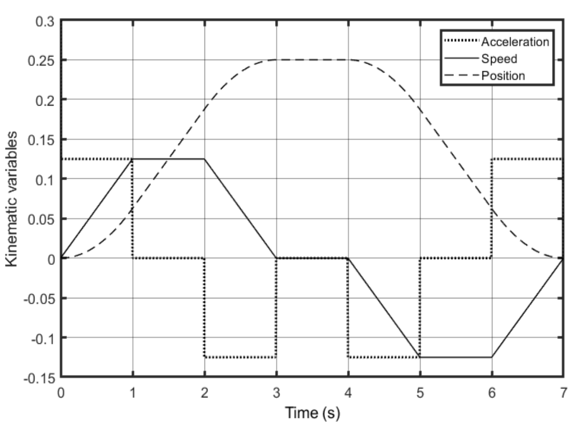
V_{max}	0,125 m/s	E_{energy}	880 Joule
a_{acc}, a_{dec}	0,125 m/s²	E_{ec}	0,2 €/year
T	2,57 Nm	T_{rms}	0,88 Nm

n_m	500 rev/min	n_{max}	750 rev/min
F_{max}	1257 N	F_{mean}	1165 N
L_{hours}	≥ 45000 hours	L_{km}	≥ 2530 kilometers
L_{cycle}	≥ $5{,}06x10^6$	L_{year}	≥ 5
E_{total}		408,36 €	

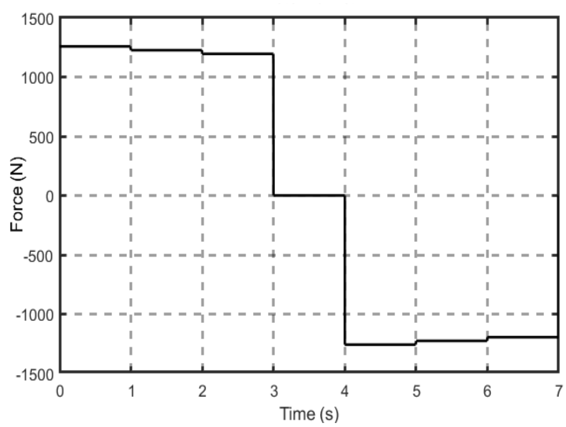
b) Pneumatic actuator

P	63339,17 N	E_{energy}	5105 kWh/year
H_{ca}	42545 m^3/year	E_{ec}	664 €/year
E_{total}		3320 €	

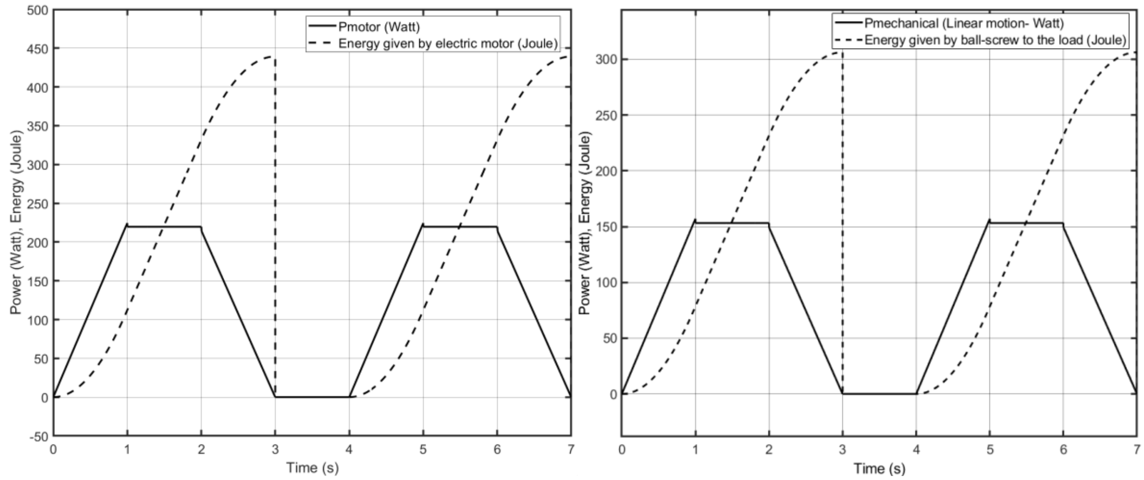
Figure 4 shows the graphical results of case study. Time response of the system variables such as kinetic , kinematic variables, energy and power responses can be followed easily from the GUI. Kinematic variables of the system such displacement, speed and acceleration



a) Kinematic variables



b) Drive force given by ball-screw to the load



c) Power and energy variation of electric motor

d) Power and energy variation given to the load by ball-screw

Figure 4. Time response graphical results of case study

4. Discussion and Conclusion

User-friendly web-based interfaces are very beneficial for selecting actuators used fluently in engineering studies, especially regarding time efficiency. In our investigations, an interface that can compare products regarding energy costs has yet to be identified. Based on the fact that product preferences can change within the scope of energy saving and sustainability, an interface development study was carried out that can make comparisons regarding energy requirements and product recommendations.

This study provides comparative content regarding the sizing selection of electromechanical and pneumatic actuators by the user's operating conditions. In addition to these specifications, the energy consumption cost of these actuator types commonly used in the industry is calculated, and a user-friendly interface study is made to present it to the end user. After the desired working conditions are entered, the values of kinematic, kinetic variables and energy consumption costs are calculated and reflected on the screen. User demands can be changed at this stage, and new evaluations can be made quickly. All variables and energy changes can be seen numerically and graphically on the screen, as defined in the case study shown in the results section.

By choosing appropriately sized actuators, it is desired to reduce the initial installation costs, contribute to sustainability by preventing the use of big-size elements necessary for environmental impact, and have the right approach to reducing energy consumption.

This study does not include actuators' initial investment and maintenance costs; it only focuses on actuators' sizing, energy consumption, and cost. It is still under development. The test bench of this system is being established, verification studies will be carried out in it. In the last stage, it is planned to present the application to the user by working on a web-based interface.

Nomenclature

a: Acceleration (m/s^2)
C_a: Dynamic load rating (N)
C_0: Static load rating (N)
d_r: Screw shaft thread minor diameter (m)
D: Pneumatic actuator diameter (m)
E_m: Output energy of the motor (J)
E_{mec}: Mechanical energy (J)
E_{energy}: Energy consumption (kWh)
E_{ec}: Energy consumption cost/year (€/year)
E_{elc}: Electric energy (J)
E_{total}: Total energy cost for working year (€)
E: Young's modulus (N/m^2)
f_s: Static load safety factor (-)
f: Coefficient determined by bearing (-)
f_{ac}: Correction factor for tolerance grades (-)
F_{mean}: Equivalent dynamic axial load (N)
$F_{friction}$: Friction force (N)
F_{ext}: Opposite force (N)
F_a: Thrust force (N)
F_{max}: Maximum static load (N)
F_{eff}:Effective equivalent axial load during phases (N)
H_{ca}: Air consumption amount a year (m^3/year)
H_{pe}: Compressed air production energy (kWh/m^3)
I: Minimum geometrical moment of inertia of the screw shaft cross section (m^4)
J: Inertia moments of the system ($kg.m^2$)
k: Safety factor (-)
l: Lead (m)
L_{cr}: Distance between mounting positions (m)
L: Critical length for preloaded nut systems (m)

L_s: Nominal service life in revolutions (rev)
L_{hour}: Nominal service life in hours (hours)
L_{km}: Nominal service life in kilometers (km)
L_{cycle}: Nominal service life in cycles (cycle)
L_{year}: Nominal service life in years (years)
L_{cyl}: Stroke (m)
m_{load}: mass of load(kg)
n: Duty cycle (1/min)
n_{crt}: Critical speed (rpm)
n_{max}: Maximum required rotational speed (rev)
$n_1,n_2,...,n_n$: Speed in phases (rpm)
n_m: Average speed (rpm)
n_h: Number of cycles per hour (cycles/h)
n_{hd}: Working hours per day (h/day)
n_{dy}: Working days per year (days/year)
n_y: Required working years (years)
N: Coefficient determined by bearing (-)
O: Operating conditions (-)
P: Buckling load (N)
P_m: Output power of the motor (W)
P_{supply}: Supply pressure (bar)
P_{atm}: Atmosphere pressure (bar)
P_{mec}: Mechanic power (W)
P_{elc}: Electricity power (W)
$q_{t1},q_{t2},...,q_{tn}$: Discrete time step for $F_{eff1},...F_{effn}$ (%)
α: Slope (°)
t: Time (s)
$t_1,t_2,...,t_n$: Time in phases (s)
T: Torque (Nm)
T_{rms}: Root mean squared torque (rms torque) (Nm)
$T_1,T_2,...,T_n$: Torque in phases(Nm)
T_{net}: Total torque (Nm)
T_m: Motor torque (Nm)
v: Speed (m/s)
x: Displacement (m)
η: Efficiency (-)
μ: Friction coefficient (-)
ω_m: Angular velocity (rpm)

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