Functional optimization of an air-car by modeling and simulation

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***Abstract* — In many technical sectors, pneumatic actuation systems are used due to their robustness, high reliability, constructive simplicity, and low manufacturing/use price. The paper highlights the components and characteristics of a pneumatic system that drives a kinematic chain. This chain sets a tricycle in motion with compressed air as power source. Modeling and simulation by mean of Automation Studio software are used for the functional optimization. Thus, the characteristics of the tricycle (speed, distance etc.) are improved by determining the components in the pneumatic diagram and simulating its behavior. The aim is to reach a maximum distance with a certain amount of compressed air.**

***Index Terms*— thermodynamic parameters, air-car, air tank, pressure regulator, air injection, control unit, energy.**

I. INTRODUCTION

Pneumatic actuation systems have many applications, but the common requirement for compressed air to be used as efficiently as possible is its reliable capacitation in tanks and its treatment. These air capacitors must first store/supply it continuously, at the required quality and at a competitive price related to the price of other sources of energy. This actuation complex must be considered from the perspective of the production costs, of the component elements and, finally, of the role it plays in the application where it is intended to serve. The components meant to be used in an application must consider at least the air supply source, the tanks, the treatment components, the pipe network, the control means, the tightness of the connections and the existence of adequate ventilation as well [1].

This article highlights an application of the pneumatic system that is used to propel a tricycle. The existing components of the tricycle are used in the application. The intention is to improve the characteristics/functionality and the performance of the pneumatic system by simulating its operation with the help of the Automation Studio software module [2].

II. DIAGRAM AND COMPONENTS OF THE SYSTEM PNEUMATIC CIRCUIT

The diagram of the analyzed/researched pneumatic system is shown in figures 1 and 2. This pneumatic complex uses a 10 liters tank that has a pressure of 200 bar, a safety circuit, solenoid valves, pressure regulator, shown in figure 1 and pneumatic cylinders, and magnetic sensors, shown in figure 2.

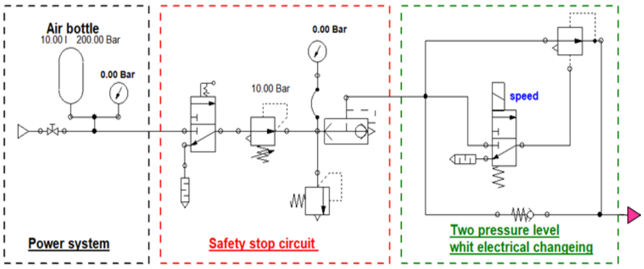

Fig. 1. Diagram of the primary pneumatic circuit used in the initial version.

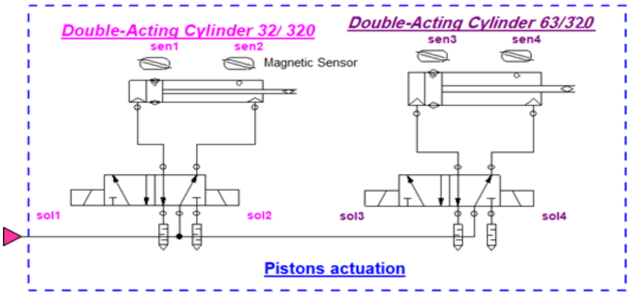

Fig. 2. Diagram of the secondary pneumatic circuit used in the initial version.

Two pneumatic cylinders and four magnetic sensors were used in the assembly presented in figure 2 as follows:

1) P1, of Ø32 with a travel of 300 mm.
2) P2, of Ø63 with a travel of 300 mm.

The kinematic drive chain of the system (tricycle) is shown in figure 3, the structure and figure 4, the kinematic diagram.

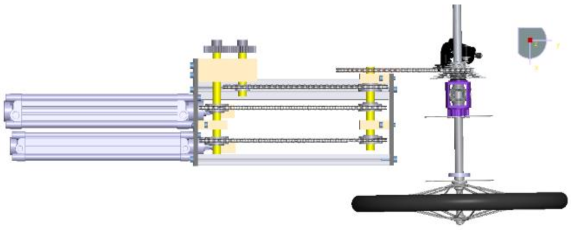

Fig. 3. Drive system, the mechanism structure.

Manuscript received XXX; revised XXX; accepted XXX.

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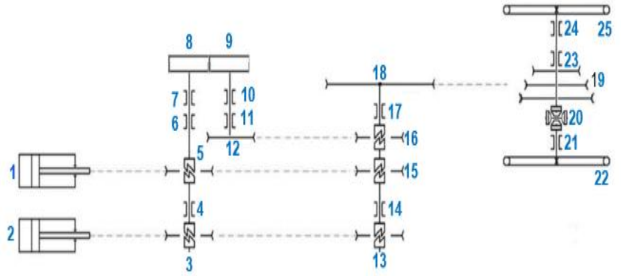


Fig.4. Drive system mechanism kinematic diagram.

Pistons P1 and P2 are directly connected to the chain drive, with gears and ratchet. The rotational motion is transmitted through ratchets 13 and 15 when the exhaust stroke of the pistons is performed. Through the ratchets 3 and 5, the movement of the wheel is transmitted when the intake stroke of the pistons is performed; the pistons change their direction through gears 8 and 9. The rotational motion is further transmitted from pinion 12 to 16 [3].

The cumulative movement is transmitted from pinion 18 to gear box 19, which is located on the housing of the differential driving gear 20, to which the rear wheel of the vehicle is connected.

The push/pull force (F) includes the following elements: pressure (P), surface area (S), load coefficient (τ) - figure 4, push and figure 5, pull.

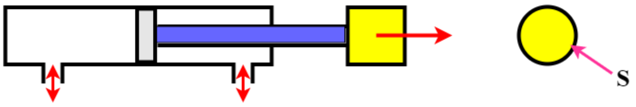


Fig. 5. Movements of the cylinder rod – push.

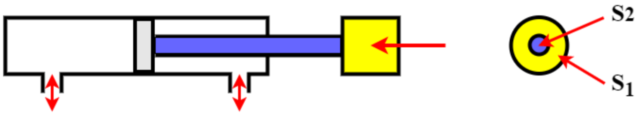


Fig. 6. Movements of the cylinder rod - pull.

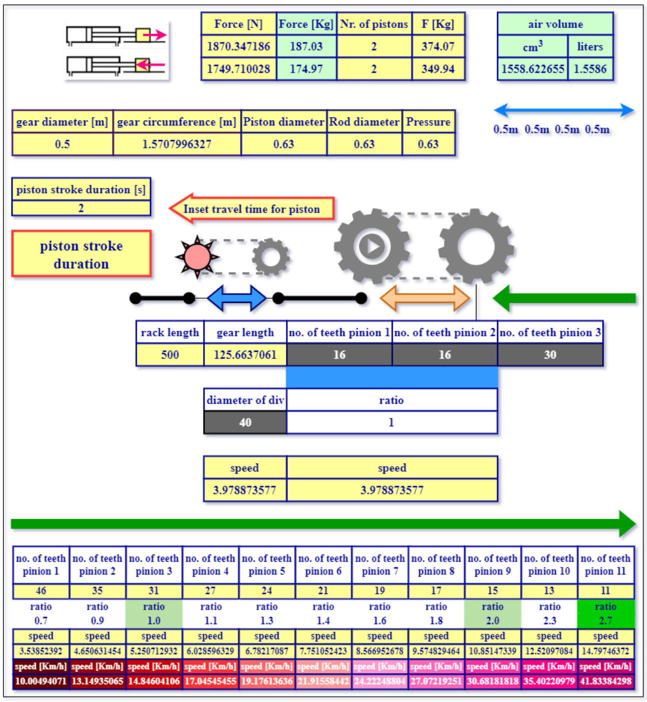
S = cylinder surface area, S1 = piston surface area, S2 = rod surface area.

The force required for actuation has the following parameters:

$$F = P \times S \times \tau \quad (1)$$

Its size is influenced by the surface area of the piston, cylinder, and rod [3].

To calculate the speed of the drive wheel over the entire kinematic chain, the average duration of the piston stroke was set at 1 s.



Force [N]	Force [Kg]	Nr. of pistons	F [Kg]
1870.347186	187.03	2	374.07
1749.710028	174.97	2	349.94

air volume	
cm^3	liters
1558.622655	1.5586

gear diameter [m]	gear circumference [m]	Piston diameter	Rod diameter	Pressure
0.5	1.5707996327	0.63	0.63	0.63

0.5m 0.5m 0.5m 0.5m

piston stroke duration [s]
2

Inset travel time for piston

piston stroke duration

rack length	gear length	no. of teeth pinion 1	no. of teeth pinion 2	no. of teeth pinion 3
500	125.6637061	16	16	30

diameter of div	ratio
40	1

speed	speed
3.978873577	3.978873577

no. of teeth pinion 1	no. of teeth pinion 2	no. of teeth pinion 3	no. of teeth pinion 4	no. of teeth pinion 5	no. of teeth pinion 6	no. of teeth pinion 7	no. of teeth pinion 8	no. of teeth pinion 9	no. of teeth pinion 10	no. of teeth pinion 11
46	35	31	27	24	21	19	17	15	13	11
ratio 0.7	ratio 0.9	ratio 1.0	ratio 1.1	ratio 1.3	ratio 1.4	ratio 1.6	ratio 1.8	ratio 2.0	ratio 2.3	ratio 2.7
speed	speed	speed	speed	speed	speed	speed	speed	speed	speed	speed
3.53852392	4.650631454	5.250712932	6.028596329	6.78217087	7.751052423	8.566952678	9.574829464	10.85147339	12.52097084	14.79746372
speed [Km/h]	speed [Km/h]	speed [Km/h]	speed [Km/h]	speed [Km/h]	speed [Km/h]	speed [Km/h]	speed [Km/h]	speed [Km/h]	speed [Km/h]	speed [Km/h]
10.00494071	13.14935065	14.84604106	17.04545455	19.17613636	21.91558442	24.22248804	27.07219251	30.68181818	35.40220979	41.83384298

Fig. 7. Calculation of the tricycle speed depending on the system parameters.

As a result of the calculations performed, figure 7, using the Microsoft Excel application, the minimum speed was measured at the value of 8.6 km/h and the maximum speed at the value of 32.9 km/h.

For the simulation with Automation Studio, it was necessary to configure the pneumatic components according to the software library, as follows:

- parameters of the cylinder: maximum pressure – MPs (bar), total volume – VT (liters).
- parameters of the pressure regulator: regulation pressure – SP (bar).
- parameters of the cylinder: extension (%), inclination – α (degrees), piston diameter -D (mm), rod diameter – d (mm), stroke – L (mm), load – M (kg).

The analyzed exhaust parameters: flow rate – Q (liters/min), working pressure – Pw (bar), acceleration - $\ddot{x}$ (m/sec^2), piston travel – dL (mm), linear movement x (m/sec), no. of strokes (dc) [4].

III. MODELING OF THE PNEUMATIC SYSTEM

The research was based on the pneumatic diagrams shown in figures 1 and 2. The operation of the system was simulated by means of Automation Studio software, the primary pneumatic circuit in figure 8 and the secondary pneumatic circuit in figure 9, introducing the known parameters; thus, the direction of the fluid flow is represented by arrows and distinct colors for different pressures (blue, red), figure 10.

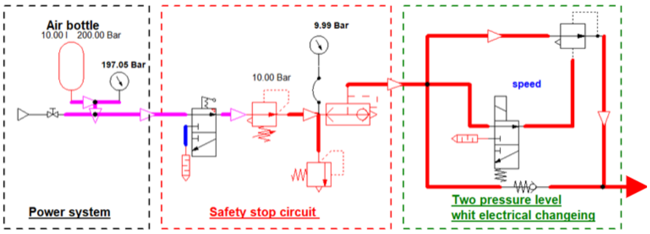


Fig. 8. Simulation of the primary pneumatic system operation.

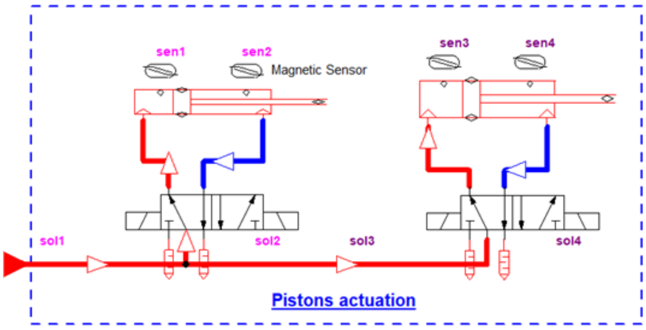
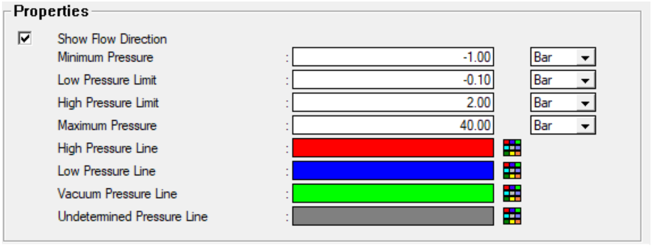


Fig. 9. Simulation of the secondary pneumatic system operation.

The flow directions and the pressure on these areas, depending on the composition and the constructive characteristics of the components, are highlighted through the simulation. They are represented by different colors according to their values, figure 10 [5].

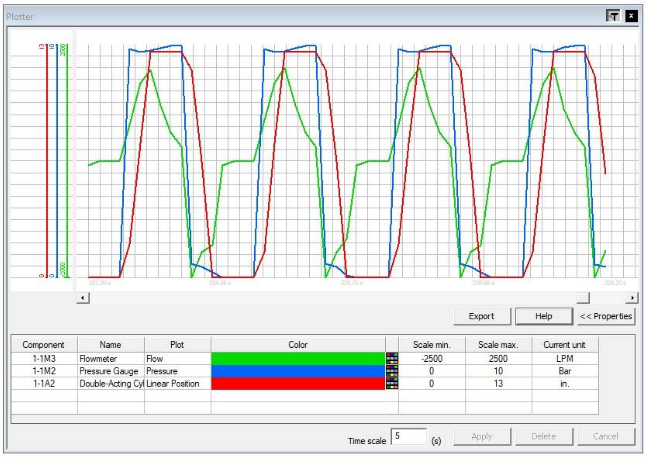

Properties

☑ Show Flow Direction

Minimum Pressure	-1.00	Bar
Low Pressure Limit	-0.10	Bar
High Pressure Limit	2.00	Bar
Maximum Pressure	40.00	Bar
High Pressure Line	🟥	
Low Pressure Line	🟦	
Vacuum Pressure Line	🟩	
Undetermined Pressure Line	⬛	

Fig. 10. Representation of the significance of colors in the program.

The following data are resulted from the simulation of the pneumatic system by means of the AS software: the tricycle can run 180 meters, for 227 seconds, Tcycle ≈ 1.25 seconds/cycle, using a maximum pressure of 10 bar, maximum flow rate: 2,500 liters/min, figure 11 [6].



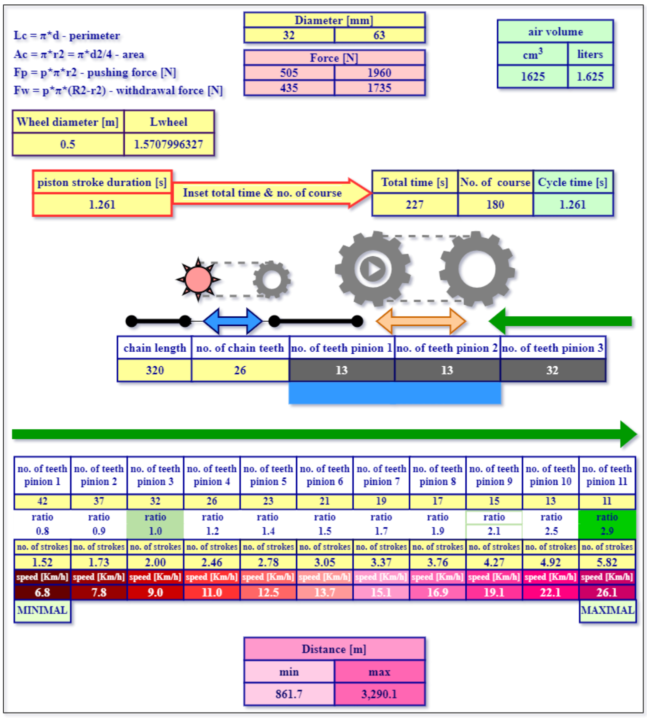
Component	Name	Plot	Color	Scale min.	Scale max.	Current unit
1-1M3	Flowmeter	Flow	🟩	-2500	2500	LPM
1-1M2	Pressure Gauge	Pressure	🟦	0	10	Bar
1-1A2	Double-Acting Cyl	Linear Position	🟥	0	13	in.

Time scale 5 (s)

Fig. 11. Values obtained by simulation.

The data obtained through simulation were entered into the excel data base and the following values were obtained, figure 12:

- minimum distance covered: 861.7 m – with the speed-change gear on the big pinion.
- maximum distance covered: 3,290.1 m – with the speed-change gear on the small pinion.
- minimum speed: 6.8 km/h – with the speed-change gear on the big pinion.
- maximum speed: 26.1 km/h – with the speed-change gear on the small pinion.


Lc = π*d - perimeter
Ac = π*r2 = π*d2/4 - area
Fp = p*π*r2 - pushing force [N]
Fw = p*π*(R2-r2) - withdrawal force [N]

Diameter [mm]	
32	63

Force [N]	
505	1960
435	1735

air volume	
cm^3	liters
1625	1.625

Wheel diameter [m]	Lwheel
0.5	1.5707996327

piston stroke duration [s]
1.261

Inset total time & no. of course

Total time [s]	No. of course	Cycle time [s]
227	180	1.261

chain length	no. of chain teeth	no. of teeth pinion 1	no. of teeth pinion 2	no. of teeth pinion 3
320	26	13	13	32

no. of teeth pinion 1	no. of teeth pinion 2	no. of teeth pinion 3	no. of teeth pinion 4	no. of teeth pinion 5	no. of teeth pinion 6	no. of teeth pinion 7	no. of teeth pinion 8	no. of teeth pinion 9	no. of teeth pinion 10	no. of teeth pinion 11
42	37	32	26	23	21	19	17	15	13	11
ratio	ratio	ratio	ratio	ratio	ratio	ratio	ratio	ratio	ratio	ratio
0.8	0.9	1.0	1.2	1.4	1.5	1.7	1.9	2.1	2.5	2.9
no. of strokes	no. of strokes	no. of strokes	no. of strokes	no. of strokes	no. of strokes	no. of strokes	no. of strokes	no. of strokes	no. of strokes	no. of strokes
1.52	1.73	2.00	2.46	2.78	3.05	3.37	3.76	4.27	4.92	5.82
speed [Km/h]	speed [Km/h]	speed [Km/h]	speed [Km/h]	speed [Km/h]	speed [Km/h]	speed [Km/h]	speed [Km/h]	speed [Km/h]	speed [Km/h]	speed [Km/h]
6.8	7.8	9.0	11.0	12.5	13.7	15.1	16.9	19.1	22.1	26.1
MINIMAL										MAXIMAL

Distance [m]	
min	max
861.7	3,290.1

Fig. 8. Results obtained (distance, speed, consumption, no. of strokes).

Following the analysis of the simulated values and of those achieved in the field with a tricycle, certain values can be amplified, for example: distance covered while keeping the air pressure constant, using a flow recuperator (directional control valve - collector) that returns a part of the dissipated energy, with the role of energy pneumatic "steering wheel".

At the same time, from a thermodynamic point of view, the pneumatic circuit is an open system that exchanges both energy and mass with the external environment (in the case of flow losses due to the lack of tightness). It can be thermally insulated, leading to energy saving [7].

One can notice from the simulations that the energy efficiency of the system is reduced, but by interconnecting some viable components (solenoid valves, automatically controlled throttles) it is possible to make circuit air consumption data logs to flatten the load curve.

To increase the efficiency of the pneumatic system, a remote management and monitoring system can be integrated, which will allow the realization of effective strategies for the use of compressed air energy. Thus, the energy consumption associated with the entire system will be reduced, under the conditions of maintaining the optimal operational parameters.

This tele management complex will analyze in real time: the consumption and distribution parameters, the distribution quality (energy efficiency), the highlighting of areas with potential defects (loss of energy), the analysis of possible failures through continuous monitoring of the optimal pressure both for operation and for early detection of losses, resulting in low costs per technical process unit [8].

IV. CONCLUSION

After modeling and simulating the pneumatic diagram by means of the Automation Studio software, the air consumption was determined. This fact helps to select the solenoid valves with an appropriate flow rate, thus increasing the distance covered. It was found out that the maximum speed of the vehicle established by simulation was close to the speed in real conditions. The air consumption resulting from the simulation is approximately equal to the real one; the vehicle travels with a compressed air tank along 2,800 m.

Future research studies may make it possible to achieve significant energy savings of 5 to 50 % [10]. It results that an improvement (even a small one) of the pneumatic circuit could lead to important financial and energy economies.

CONFLICT OF INTEREST

The submitted work, named "Functional optimization of an air-car by modeling and simulation" was not carried out with a conflict of interest. The authors declare no conflict of interest.

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