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SIMULATION OF PNEUMATIC SYSTEMS USING AUTOMATION STUDIO™ SOFTWARE PLATFORM

Ghinea, M.; Agud, M. & Bodog, M.
University POLITEHNICA of Bucharest, Splaiul Independentei, 313, sector 6, 060042, Bucharest, Romania
E-Mail: ghinea2003@yahoo.com, agudmmihai@gmail.com, mircearechi@gmail.com

Abstract
Nowadays, more and more industrial applications use pneumatic systems instead of hydraulic, electrical or mixed systems. This article presents the applicability of pneumatic engines for compressed air vehicles (CAV) from the perspective of their simulation on the Automation Studio software platform. It is desired to use the mechanical work produced by only pneumatic cylinders taken over by a mechanical system that transforms the linear motion into a rotational one, this helping to propel the CAV. A feature of this engine is the limited quantity of compressed air at disposal (a reservoir). Also, the most efficient operation of the pneumatic cylinders is studied to achieve the operation with low consumption of compressed air, thus leading to increased performances. The current simulation was run without the use of specific electric/electronic equipment (PLC /PACs). Therefore, the pneumatic devices had assured the command and control of the system.

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Key Words: Pneumatics, Simulation, Pneumatic Engine, Mechatronics, Automation Studio

1. INTRODUCTION

At the end of the 19th century, the internal combustion engine was conceived. This engine, still in use today, works on the principle of burning fossil fuel to create mechanical energy. Although very efficient, this has been questioned for years, given that the energy used for its operation is not renewable but very polluting [1]. Today, experts estimate that in less than 50 years fuel reserves will be depleted entirely [2]. In addition to this depletion of oil reserves, the global warming problem caused by the release of greenhouse gases urges a reassessment of the method of engine operation.

Engineers have begun working on pneumatic propulsion, especially on pneumatic engines (PE) [3, 4]. Using pneumatics or any other type of source of energy to make an engine work means producing mechanical work [4]. In physics, mechanical work is the amount of energy transferred by force. Performing mechanical work requires the application of kinetic energy on an object that opposes a resistance and must be moved. In a pneumatic system, energy is stored as compressed air at different pressures. The working energy in a pneumatic system results in such mechanical work when the compressed air expands and/or retract. Most pneumatic systems rely on a constant supply of compressed air to make them work. The source can be an air compressor or, in some cases, a pressure vessel. In the compressor case, the air is sucked out of the atmosphere and then stored in a high-pressure tank called receiver [4-6]. Then, the compressed air is supplied to the system through a series of specific pneumatic components.

The term "aircar" (a car with a PE) *or Compressed Air Vehicle – CAV* is not new. Many car producers have tried to produce a car with a PE. Worldwide, Motor Development International, Zero Pollution Motors, or Tata Motors are just a few companies trying to bring cars with PE to market. However, a thorough analysis of the aircar advantages and disadvantages is not covered by this paper, as its aim is rather to bring into the general attention a specific type of PE used on prototypes in an international academic CAVs competition. The engineers are encouraged to find an innovative technical solution for achieving motion by transforming linear into a

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rotating one when a PE is used. The transmission of motion from the PE to the wheels, the electronic control, the steering control, and the entire CAV body design, are up to each producer apart [4].

In 2017 the Laboratory for Pneumatics was opened in the Faculty of Industrial Engineering and Robotics from University Politehnica of Bucharest. As Industry 4.0 embodies the future of technology, we do consider that Pneumatics must be a part of it [7]. Thus, in order to increase visibility and gain credibility, the team works on attracting industrial partners willing to contribute to the development of some industrial pneumatic applications.

2. SCIENTIFIC CONTEXT

2.1 Simulation on the software platform

The greatest difficulty when working with Pneumatics derives from gas characteristics and behaviour. The control of a compressible gas is a sensitive and complex issue, and consequently, the speed and acceleration of pneumatic devices are difficult to manage too. Additional devices must be included in the pneumatic system to accomplish the technological and scientific goals. Thus, the model gains in complexity, a fact that requires knowledge and innovation, and additional funds as it often translates into additional cost. More than that, the compressed air can be easily contaminated and therefore, the risk of damaging the pneumatic devices is high, causing a shorter lifetime [8]. Besides, it produces a lot of noise during exploitation, and if the system uses gases harmful to the environment, the risk of contamination must not be overlooked.

The science of Pneumatics is not at hand for engineers because of the necessary knowledge concerning fluid mechanics, which is a prerequisite for designing and using industrial pneumatic systems. Despite these drawbacks, and many others as well, the inexhaustible air source constitutes a considerable advantage. Plus, the air is free and non-flammable by its nature, and the technological leakages do not have catastrophic consequences on people and the environment [8, 9]. The cost-effectiveness is essential, but the used materials for Pneumatics are cheap. Only the knowledge necessary to design these systems can raise the price (computer simulation is mandatory during the design stage as well as the prototyping pneumatic systems) [9].

In what this research is concerned, due to the low number of technical variables of the gas, the computer simulation was not so complicated. There is only the uncontrollable behaviour of the gas during its utilisation that causes design problems. Concerning this, the used version of the Automation Studio software platform offers benefits, facilitating the creation of a performant pneumatic system [10].

2.2 Considerations on a simple CAV model

The main used device is the double-acting pneumatic cylinder [11, 12]. Starting from the designing rules and the definition of the pneumatic system, we must establish optimal utilisation conditions [13, 14]. The engine can contain one, two or more cylinders that receive compressed air from a standard 10 litres pressure tank at 200 bar [15, 16]. The supplied linear motion must be transformed into rotation motion to move the PE prototype. In accordance with AS software, this simple pneumatic system can be defined as in Fig. 1.

The PE must undergo several restrictions: to contain pneumatic cylinders only, additional power sources not being allowed; a buffer container can be used connected to a pneumatic circuit by 3/2 valve. The main goal is to obtain a running span as long as possible at specific values for speed and acceleration. For that, the running parameters of the pneumatic engine must be very well controlled, independent of all the external factors that determine the loosing of the obtained mechanical work. A performant PE goes hand in hand with a smaller quantity of consumed compressed air, which means a lower amount of energy consumed for the same purpose. The same strategy can also be implemented in industrial pneumatic lines to reduce the quantity of used compressed air [17]. The proper control of the pneumatic system can lead to a smaller amount of energy used to obtain the necessary compressed air.

UPB's academic team designed its prototype of CAV using a simple pneumatic engine. It has a 120 kilograms maximum load, including the driver. In this paper, we do not study the influence of the total friction force produced by the mechanical gear and devices as energy consumers. In order to obtain the targeted results, proper cylinders, valves and other pneumatic devices were chosen, and the appropriate operating parameters of the compressed air were adjusted. Consequently, the study was conducted in set ideal running conditions.

According to the rules of mechanical system design methodology together with the research on PE, to obtain a performant CAV, the following should be established and calculated too:

1) the kinematic structure of the mechanical chain, number of wheels, type of – gearbox, type of brakes etc.,
2) the mechanical load, the energy lost by friction between wheels and road, the weight of the entire assembly (prototype, driver, compressed air tank etc.),
3) the travel conditions (speed, distance proposed to be covered with 10 litres at 200 bar)[15].

After that, the proper propulsion can be established, meaning:

1) the type and number of the actuators (pneumatic cylinders),
2) the types of valves and other pneumatic devices,
3) the type of compressed air control: (a) pneumatic by valves and amplifiers, (b) electronic by PLC/PACs,
4) all the important parameters of the compressed air from the tank towards the first mechanical devices, which must: (a) transform the linear motion into rotational one, (b) provide enough energy to move the prototype with the desired travel parameters.

3. THE SIMULATION WITH AUTOMATION STUDIO

Despite that Automation Studio (AS) is a professional software platform for simulation of the pneumatic systems, there is not too much scientific work in the worldwide literature regarding its application. For actual and future studies, we use the package for Pneumatics and PLCs control of the AS Educational v. 6.4.

3.1 Pneumatic scheme and a technical description

In Fig. 1 there is a simple model of a PE with only one pneumatic cylinder, used the specific conditions imposed by the competition rules and design restriction: (a) the control and command of the system are pneumatic, (b) it will be considered a global load of the CAV (including the driver), (c) just basic components are used.

The pneumatic symbols used in Fig. 1 are in accordance with International Standard ISO 1219-1 [18]. Their description follows: 1 – Pneumatic Pressure Source, 2 – Normally Open Shut-Off Valve (2-Way), 3 – Filter and Separator (Automatic), 4 – Lubricator, 5 – Thermometer, 6 – Gas-Loaded Accumulator without Separator (reservoir), 7 – Pressure gauge, 8 – Flowmeter, 9 – 3/2 Directional Valve, 10 – Pressure Reducing Valve, 11 – Pressure Relief Valve, 12 – Pressure gauge, 13 – Quick Exhaust Valve, 14 – Spring Loaded Check Valve, 15 – 3/2 Directional Valve, 16 – Remote Pressure Reducing Valve, 17 – Pressure gauge, 18 – Pulse Counter, 19 – 5/2 Directional Valve, 20 – 3/2 Directional Valve, 21 – 3/2 Directional Valve, 22 – Quick Exhaust Valve, 23 – Quick Exhaust Valve, 24 – Double-Acting Cylinder.

Fig. 2 shows the image of the real PE, with the identification of the pneumatic components. The pneumatic pressure source (compressed working gas) acts as a pressure generator.

In our PE, this source is a volume-limited one (the reservoir – 6) [5]. It assumes that gas from the gas tank is well prepared and without impurities, so that a station for air preparation and supply can be missing (1, 2, 3 and 4). Generally, all pneumatic components need to be lubricated to work well and have a proper life span, although there are also some not needing lubrication. The latter are rather self-lubricating. The pneumatic device of this type has a built-in lubrication system that is based on long-lasting solid lubricants or has an internal oil source, both of which allow the device to withstand the passage of air through the interior [19]. The best way to achieve this is to install an independent lubricator or as a part of a gas preparation station.

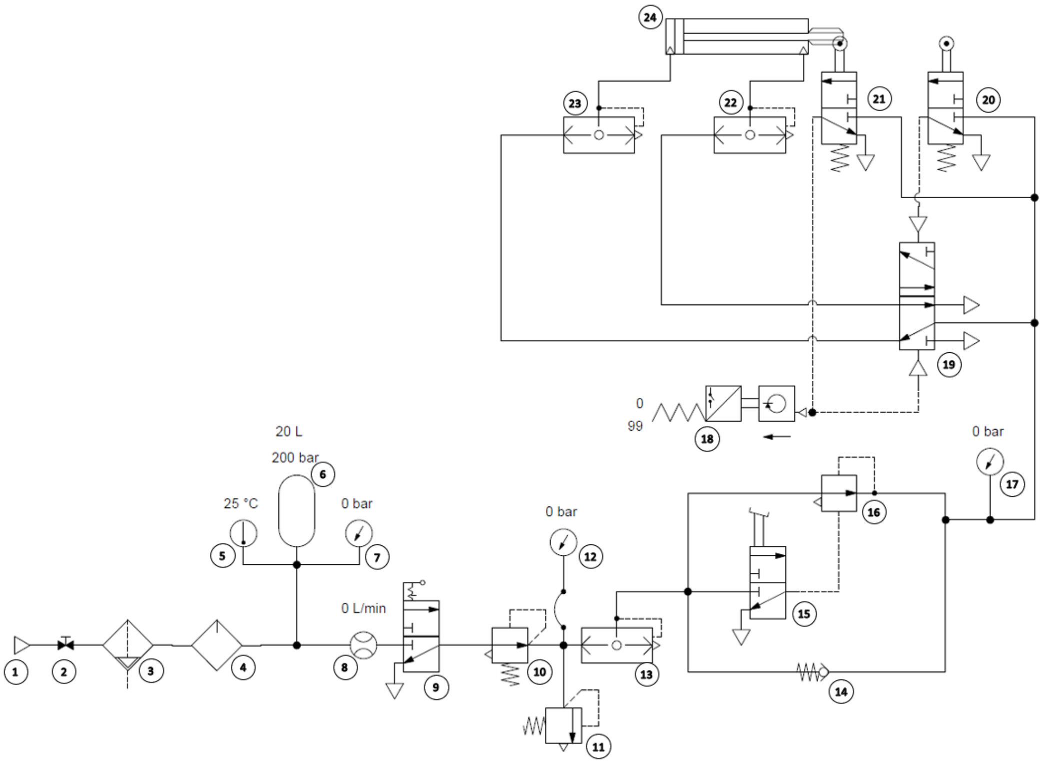

Figure 1: The pneumatic scheme of the PE using AS software platform.

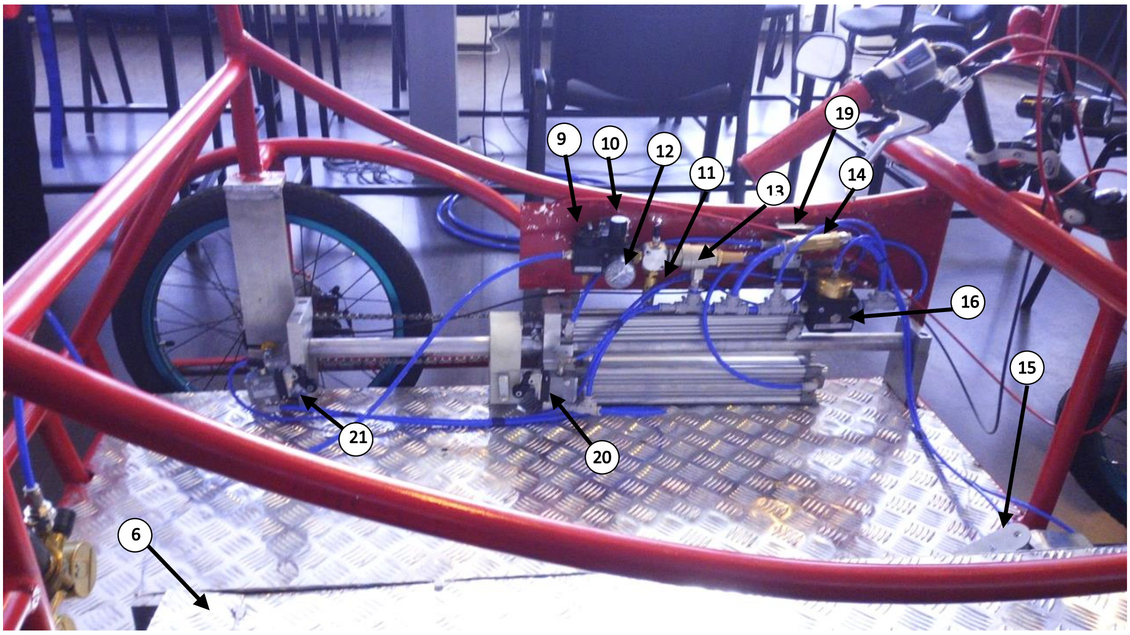

Figure 2: The pneumatic engine (two cylinders version).

This lubricator will allow constant and automatic lubrication to the correct level. Oil is atomised into the compressed air flow, which transports the resulting oil mist to the component requiring it. All over the pneumatic system, it is essential to install a lubricator as close as possible to the component that requires lubrication so that oil mist condensation is reduced to a minimum level [10].

The pressure and temperature are controlled by 5 and 7. The reservoir is filled with 10 litres of gas at 200 bar. The principle behind its behaviour is simple and based on the high compressibility of the gas inside. Therefore, gas volume variation is much more important than its pressure variation. During discharge, the gas pressure is pushing the accumulator's fluid out, and because of the high gas compressibility, the pressure will slightly vary.

In this case, when 6 is the primary pressure source, another accumulator – buffer can be used (still not used in this paper because of the reason described in #2). This buffer can have a role against the undesirable phenomenon appeared when the pressure in 6 is too high. Within an isothermal process, it considered that gas temperature remains constant, in order to reach the thermal equilibrium (the change from one state to another is not so fast) [4]. Thus, in an ideal gas case, the following relation can be used:

$$P_1V_1 = P_2V_2 = K \tag{1}$$

where: P_1V_1 are the values characterising the initial state, and P_2V_2 – the values related to the other/final state, and K a constant value. The adiabatic process is the process within which there is no heat transfer between gas and the environment. The thermodynamics equations for this process when the gas behaviour is modified from one state to another are the following:

$$P_1V_1^{\gamma} = P_2V_2^{\gamma} = K \text{ or} \tag{2}$$

$$T_1V_1^{\gamma-1} = T_2V_2^{\gamma-1} = K \tag{3}$$

where: P, V and T are the pressures, volumes and temperatures in the initial and final state, and γ is the adiabatic exponent (ratio between the specific heat at constant pressure, respectively, at constant volume of the gas accumulator) [20].

In a polytropic process, the gas might exchange heat with its surrounding, but the change from one state to another is not slow enough to allow thermal equilibrium. The theory and the AS use two different ways to simulate the polytropic behaviour of the gas in an accumulator. The former uses a value of γ that takes into consideration the heat exchange with the fluid and/or container while keeping the values of the heat transfer coefficients at zero. The latter uses the adiabatic value, γ and two heat transfer coefficients: the first from between the gas and the wall of the reservoir, and the other from between the wall of the reservoir and the outside environment [10]. The effect of the heat transfer on the gas temperature is calculated using the dimensional characteristics of the accumulator to approximate the heat exchange area. The gas pressure can be calculated by using this final value of the temperature. The effect of heat transfer on the temperature of the fluid in the pneumatic system can be overlooked.

The elements 5, 7, 12, 17 and 8 are instruments that measure the pressure, the flow and temperature of the gas in the accumulator during the engine running. Usually, 5 and 8 are used in the industrial pneumatic system, but 7, 12, 17 are instruments that measure the flow going through research pneumatic systems.

The directional valves DV are devices used to direct the flow of the fluid. These can be operated by a human operator, a pilot fluid, by an electrical signal or by mechanical contactor (electromechanical systems) [21].

The 3/2 directional valve 9, 15, 20, 21 and the 5/2 directional valve 19 are operated with manual (non-electronic) control, and the standard available controllers are the lever, pedal, joystick and several types of buttons. To avoid any confusion and to simulate a pneumatic model correctly, AS offers the same representation (real image, the symbol, and parametrisation) for all pneumatic components.

These components are important for the control of the pneumatic systems because they are devices that receive a certain amount of fluid in a reasonable time, thereby creating a logical sequence [21]. The valve 10, from detail A, in Fig. 4, works as a pressure regulator that maintains the constant pressure at its output (even if the input pressure varies) and 11 blocks the fluid flowing from IN port (INp) to the OUT port (OUTp) when the pressure is not high enough at INp. When this pressure is equal or greater than the safety pressure, the gas flows from INp to the OUTp, which is already connected to the exhaust. The valves 13, 22 and 23 are quick exhausting valves (QEV) which allow the fluid to circulate from INp to the OUTp when the INp is equal or great than OUTp. When INp > OUTp, the gas goes from OUTp to the OUT reservoir (OUTr). In the Technical Specifications of AS software, there are indicated the specific curves necessary to calculate the decreasing of the pressure for both flow directions during the simulation. Practically, it can be seen in the model that QEV is mounted on the supply port of a pneumatic cylinder and allow normal gas flow from the DV to the cylinder. When the gas must go in the opposite direction, it should not achieve the valve because QEV will expulse it. The check valve 14 allows the gas to flow from INp to the OUTp if the pressure at INp is greater than or equal to the safety pressure. By this valve, the flow is blocked from OUTp to INp.

The valve 16 is a pressure regulator that maintains a constant OUT pressure, even if IN pressure varies. The pulse counter 18 is used to count impulses. In our experiment, this is used to record the double strokes (expansion and retraction of the piston). This vital output parameter can be used later to calculate the performances of the PE [21].

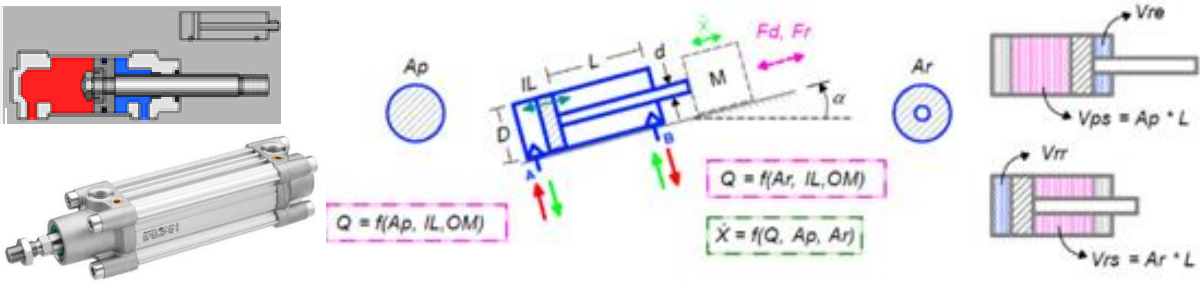

Figure 3: The theoretical presentation of the double-acting cylinder in AS [10].

As in many pneumatic installations and hydraulic as well, also in our system, the most important component is the double-acting pneumatic cylinder 24 (Fig. 3) [10, 22]. It is used when pneumatic energy must be obtained during the rod movement in both directions. A_p is the piston area on the left side; A_r is the piston area on the right side ($A_r = A_p - A_{rod}$); IL is the internal length on the left chamber; D is piston diameter; d is rod diameter; A and B are the IN/OUT points of gas admission on the left, respectively, the right side of the cylinder; L is the length of the right chamber (piston stroke); and M represents the total load that must receive the mechanical work produced by the cylinder. Q is the gas flow, $\dot{x}$ is the speed of the piston, F_d is the extension force, and F_r is the retracting force. V_{ps} and V_{rs} are volumes in the left, respectively right chambers, during the gas expansion and V_{rr} and V_{re} are the volumes in both chambers during the gas compression [14].

Figs. 4, 5 and 6 show the four steps of the functioning cycle of the PE. The colours imposed by the software platform have the following meaning:

– for pressure appearance, **brown** – maximum pressure, **red** – high pressure, **blue** – low pressure;
– for flow appearance, **brown** – high flow, **red** – medium flow, **blue** – low flow.

The first step consists of the gas accumulator loading until 10 litres and 200 bar, while during the second step, the gas goes through engine being stopped by the directional valve 15.

As can be seen in Fig. 2, the valve 15 is driven by a pedal, identically with the acceleration pedal in the classic automobile case.

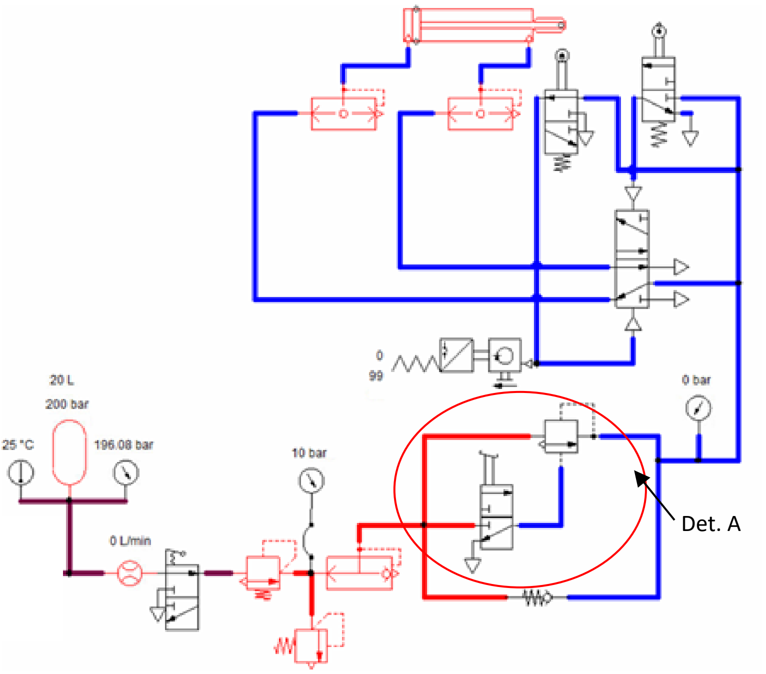

Figure 4: The starting time – the gas is released from the source toward the PE (Red lines indicate the moving gas, blue lines indicate the stationary gas).

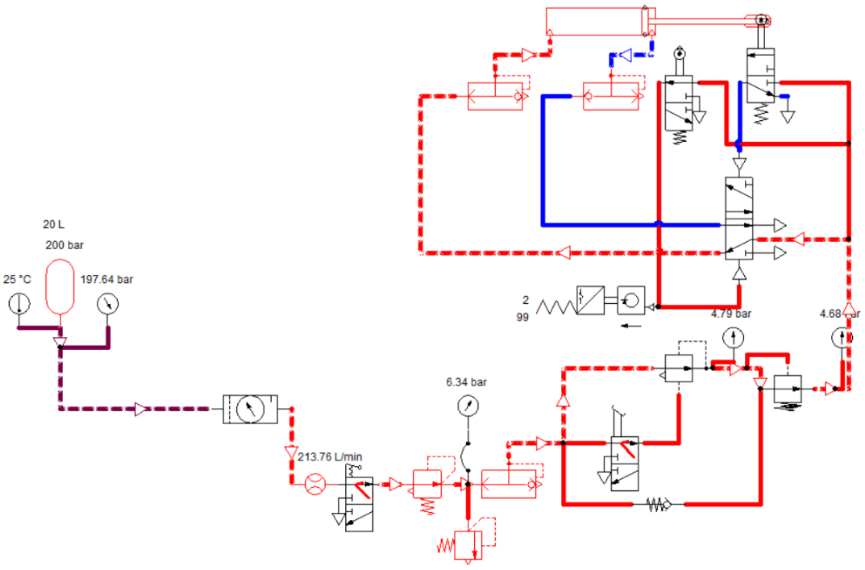

Figure 5: Step three – the piston rod is pushed outwards (from left to right).

In step 3, the gas enters in the left chamber of cylinder pushing the piston rod outwards and producing mechanical work. The displacement happens until the rod touches the roller of the valve 21. Step 4 represents the backward/retracting movement of the piston, gas filling the right chamber via devices 19 and 22 until the valve 20 is touched. After that, the steps 2-3-4 are repeated in a loop until the gas from accumulator runs out. If the pedal mounted on the valve 15 is pressed all the time, only the steps 3-4 are repeated.

The dashed lines indicate:

- the command given by 15 to produce pressure through the rest of the system and
- the commands given by 20 and 21 on 19 to create the expansion, respectively retraction, of the piston [10].

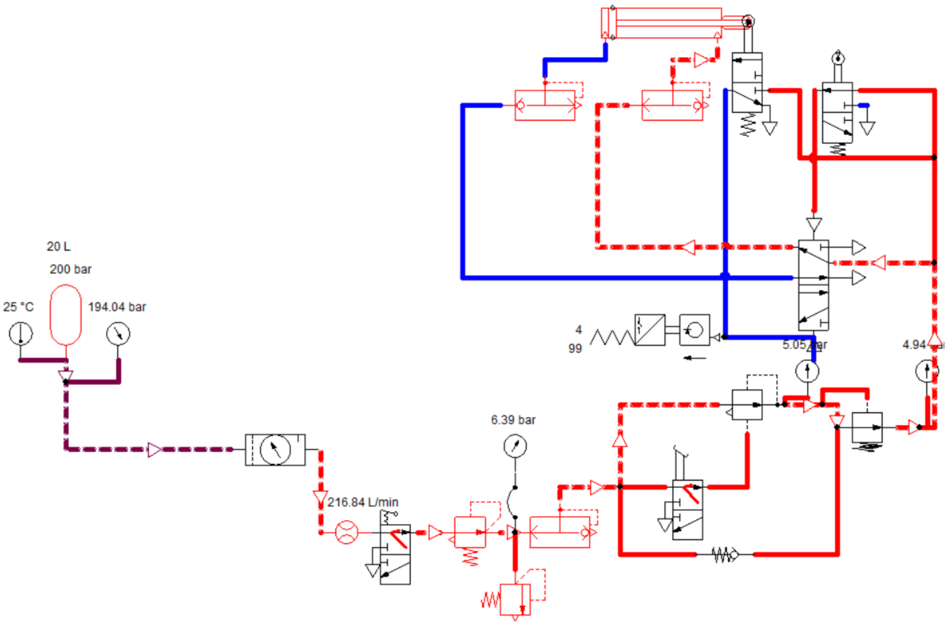

Figure 6: Step four – the piston rod is retracted inside the cylinder (from right to left).

3.2 Parametrisation and simulation

Usually, in the typical engine case, before starting functioning, the state of all pneumatic devices must be checked, and also the gas accumulator parameters, the entire mechanical set-up and the presence of the safety system protecting the pneumatic system against dangerous high pressures as well.

For the simulation with Automation Studio, it is necessary to set-up the pneumatic components according to the software library:

– **the gas accumulator parameters**: Precharge Pressure – p_o [bar], Total Volume – V_T [litre], Maximum Pressure – M_P [bar]; type of accumulator, type of Circuit and Installation.

– **the cylinder parameters**: Extension [%], Inclination – α [deg], Piston Diameter – D [mm], Rod Diameter – d [mm], Stroke – L [mm], External Load – M [kg], Pull External Force – EF_{pll} [daN], Push External Force –EF_{psh} [daN], Maximum Pressure – MP_p [bar], type of cylinder, type of Circuit and Installation.

– **the pressure reducing valve parameters:** Setting Pressure – SP [bar], Maximum Pressure – M_{Pprv} [bar], type of valve, type of Circuit and Installation.

As output parameters, one can record (using the AS measurement precision): **absolute flow** – Q [l/min], **working pressure** – P_w [bar], plottable parameters, as well (Fig. 5): Acceleration – $\ddot{x}$ [m/sec^2], Linear position – d_L [mm], Linear speed – $\dot{x}$ [m/sec], **pulse counter** – [dc – no. of pulsations]. This last parameter indicates the number of double strokes of the piston. Due to this parameter, the entire distance covered by the default quantity of gas can be computed (see the next chapter and future work).

Our pneumatic model contains just the mandatory pneumatic devices that assure the running of the PE. Once again, it is worthy of mentioning that this model can also be used in an industrial pneumatic system, using either a limited volume in the gas accumulator or unlimited gas supply. For simplicity and to obtain accurate results, a pure pneumatic system was used, thus being avoided the Pneumatics and Electronics blended, a situation that will be studied in the future work. Therefore, the command and control of the engine are also assured by pneumatic components. Following the three steps presented in Fig. 4, the energy of the gas under pressure was used to obtain mechanical work necessary for moving the prototype and reaching the best performance (speed and covered distance).

For the present study, it was used by turn several cylinders belonging to the same category of a double-acting pneumatic cylinder, differing only by the piston diameter, *D*. Also, the external load *M* was different, in order to check the impact that the real weight of the prototype might have in different circumstances (see Table I).

Table I: Recorded data of the simulation.

Pneumatic cylinder	***dc***	**Total time** [sec]	MP_p [bar]	***Q*** [l/min]	$\dot{x}$ [m/sec]	$\ddot{x}$ [m/sec^2]	**Average time/cycle** [sec]	**Travel distance min*** [m]	**Travel distance max*** [m]	**Speed min** [km/h]	**Speed max** [km/h]
-1-	-2-	-3-	-4-	-5-	-6-	-7-	-8-	-9-	-10-	-11-	-12-
V_T [l] = 10, p_o [bar] = 200, M_{Pprv} [bar] = 10, *D* [mm] = **63,** *L* [mm] = 320, *M* [kg] = 120	204	253	10	336	2.44	41,28	1.24	65.28^a 130.56^b 976.6^c	3728.8^c	6.9^c	26.5^c
V_T [l] = 10, p_o [bar] = 200, M_{Pprv} [bar] = 10, *D* [mm] = **63,** *L* [mm] = 320, *M* [kg] = 100	210	244	10	346	2.51	43.04	1.162	67.2^a 134.4^b 1005.3^c	3838.5^c	7.4^c	28.3^c
V_T [l] = 10, p_o [bar] = 200, M_{Pprv} [bar] = 10, *D* [mm] = **63,** *L* [mm] = 320, *M* [kg] = 0	207	214	10	466	4.62	55.16	1.034	66.24^a 132.48^b 990.9^c	3783.6^c	8.3^c	31.8^c
V_T [l] = 10, p_o [bar] = 200, M_{Pprv} [bar] = 10, *D* [mm] = **100,** *L* [mm] = 320, *M* [kg] = 120	137	157	10	494	1.69	31.5	1.146	43.84^a 87.68^b 655.8^c	2504.1^c	7.5^c	28.7^c
V_T [l] = 10, p_o [bar] = 200, M_{Pprv} [bar] = 10, *D* [mm] = **100,** *L* [mm] = 320, *M* [kg] = 100	140	154	10	498	1.67	32.2	1.1	44.8^a 89.6^b 670.2^c	2559^c	7.8^c	29.9^c
V_T [l] = 10, p_o [bar] = 200, M_{Pprv} [bar] = 10, *D* [mm] = **100,** *L* [mm] = 320, *M* [kg] = 0	138	149	10	682	2.64	52.82	1.08	44.16^a 88.32^b 660.6^c	2522.4^c	8.0^c	30.5^c

Other variables used in the simulation are Stroke, *L* and few parameters of the mechanical system connected between the piston rod and the prototype wheels. In Table I, there are shown the output parameters obtained for a specific transmission ratio in the mechanical system. The main output size, *dc*, obtained from Pulse Counter 18, that was transformed by mathematical relations into total Travel distance of the prototype and its minimum and maximum speed as well, for two different remarkable loads (*M* = 100 kg and 120 kg) and idling (*M* = 0 kg).

There are three different situations when the Travel distance is measured: when the mechanical work is used only during the "OUT" rod motion (expansion), and not during the "IN" rod motion (retraction, case ^{a}); when the mechanical work is used in both situations, OUT/IN rod motion (case ^{b}); and when the output values depending on the mechanical mechanism linked by the cylinder rod (case ^{c}).

These important output parameters depend on internal pneumatic parameters and the all CAV mechanical components (the kinematic structure of the mechanical chain, number of wheels, type of – gearbox, type of brakes etc.) as well. Here an internal/external gear for sport bikes can be used. Achieving a large range of torques that indirectly can improve gas consumption requires a certain number of pinions. The UPB's prototype uses a Shimano internal gear hub with 11 pinions.

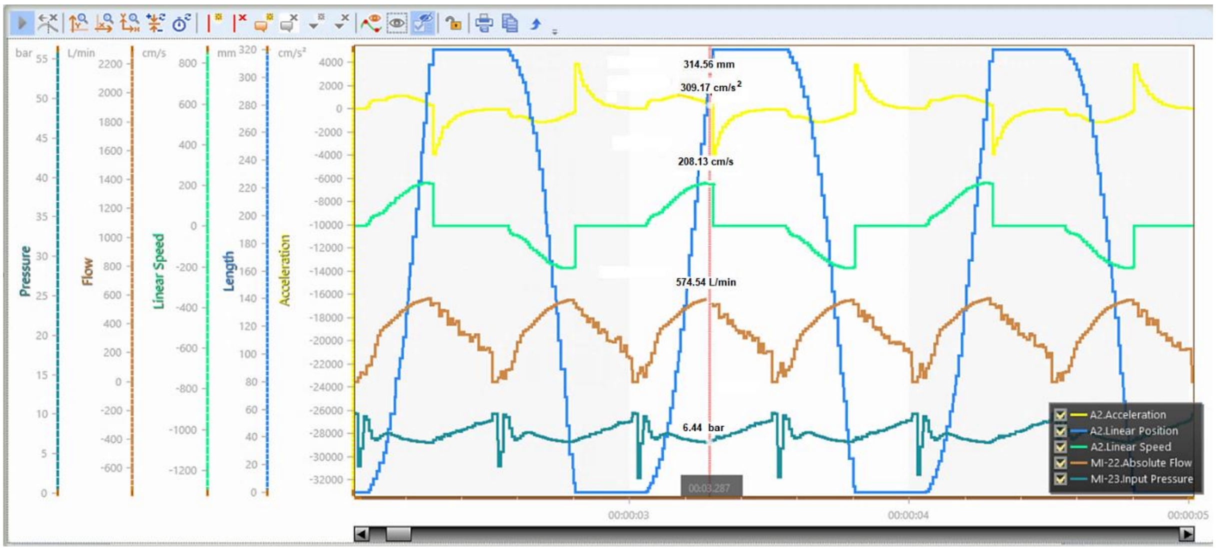

Figure 7: The graphs obtained in AS for the most important variables during the simulation.

The values in Table I are important for several reasons. As already mentioned, many pneumatic components cannot be adjusted during the system running, as they cannot be adjusted in a real installation as well. Therefore, we can change that component with another one belonging to the same category. According to the rules of the above-mentioned competition, we cannot change the imposed parameters of the gas from the reservoir 6, only the way we conceive the operation of the pneumatic cylinder.

The real-time behaviour of the important studied parameters is shown in Fig. 7. Even if superimposed, the curves for MP_p, Q, $\dot{x}$, $\ddot{x}$ and L can still be studied separately, function of the AS settings. These graphs can be recorded and studied for any simulation after the desired parameters have been modified.

4. CONCLUSIONS AND FURTHER RESEARCH

The present study aims to contribute to the improvement of the pneumatic engine performance. It is a technical and scientific challenge, mainly because of the limited amount of gas that can be used. At the 13th edition of the Pneumobile aircars competition (2017), the team of the Politehnica University from Bucharest, Romania, achieved average performances in terms of results. There are three races in this competition: speed, long-distance and skills. The present study is relevant for the result of the first two races, as generally, competitors try to achieve the highest speed and distance covered by using the same gas accumulator at the same imposed parameters.

Our purpose is to design a pneumatic engine able to produce as much mechanical work as possible for moving the prototype over a longer distance. Concerning the prototype speed, this is analysed from the point of view of its maximum level achieved in the already stated conditions. The used model is as simple as possible, and this undoubtedly leads to the high accuracy of the output data. Thus, these results are reliable for a thorough analysis of the CAV performances.

Related to the simulation outcomes, it can be observed that the differences between all the three cases are not so important regarding the Travel distance and Speed measurement (up to

10 %), but are really important (up to 70 %) for the piston speed (column 6) and acceleration (column 7). Therefore, some important conclusions can be drawn:

1) the pneumatic components of the prototype engine have been chosen or adjusted incorrectly,
2) the mechanical load had a different value compared to the values used in the simulation,
3) the gas consumption adjusted by the driver using the direction valve 15 was different from the optimised gas consumption in the AS simulation,
4) the race route had an influence on the driver's decisions regarding the utilisation of the PE.

The results obtained by the UPB prototype (2821 km for Travel distance and 23 km/h for Speed) are significantly different from those obtained by running the simulation presented in this article, despite the fact that the PM used on the UPB prototype (D = 63 mm, M = approx. 120 kg) is almost the same with that used in the simulation. These differences are due to the friction between the mechanical components that belong to the system for transforming the motion from linear to rotating and due to the friction between the wheels and the ground. In addition, a significant amount of gas was lost from valve 15 ("accelerator pedal"), as it is difficult to control this valve by only the driver's foot.

As already mentioned, for the sake of the accuracy, the simulated model was intentionally chosen as simple as possible. However, this theoretical model can gain in complexity by adding: (a) pneumatic devices for improving the use of gas, (b) electronic control and command of the system, (c) decreased of human interference with the pneumatic engine, (d) experience in using the AS system.

Finally, to improve the performances of the CAV, an improved mechanical system is needed, so that to use mechanical work as efficient as possible.

As already mentioned, the present studied model used only one pneumatic cylinder; command and control are also pneumatic, without any electric or electronic circuit. This kind of installation can be successfully used in any industrial architecture, especially in dangerous and explosive environments. Regarding the simulated PE, this will be redesigned by using more cylinders, a PLC / PAC control to adjust the gas consumption and increase its rapidity, and an appropriate and studied linkage between pneumatic components. The more simulations in Automation Studio are performed, the sooner expected results will appear, namely a more precise PE, and respectively a more performant CAV.

The last phase of our researches will evaluate the complete behaviour of the CAV and solve the reciprocal influences between the PE and the rest of the mechanical structure of the CAV. Technically speaking, it will be studied the influence of the several structures of taking over and distributing the movement from the piston rod to the system of transformation of motion from translational to rotational one, and then taking over the move by the wheels of the machine. An important step will be the pneumatic devices electronic control, considering the challenges raised by the unpredictable behaviour of the compressed air. Some unmeasurable errors could appear during the simulation causing important differences in the expected outcomes.

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