Optimization of compressed air consumption in a pneumatic vehicle

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Abstract. The aim of the research described in the article was to optimize compressed air consumption in a pneumatic driven vehicle to achieve the maximum traveled distance and maximum acceleration over a short distance. The Pneumatic vehicle was equipped with a 10-liter tank. The vehicle drive system consists of an actuator, a reciprocating movement which is converted into rotary motion and transmitted to the road wheels. The article analyses the impact on the range and maximum speed of a pneumatic vehicle based on parameters such as gear ratio, the amount of air supplied to the actuator, opening the drain valves before the piston reaches dead center, setting on the reduction valve, size of the buffer tank, and gear shift time. After the initial analytical estimation of the actuator operating parameters, a numerical analysis of the vehicle operation of the pneumatic and drive systems of the vehicle was performed in the Simcenter Amesim program. In this program, a pneumatic system model was created together with the vehicle drive system. Finally, conclusions from the simulations are presented, showing how the pneumatic system should be built and how it should be powered to obtain the maximum range and the greatest acceleration of the vehicle.

1. Introduction

Nowadays, alternative ways of powering vehicles are being searched for. One possibility is the pneumatic drive, which was used in cars and trams from the end of the nineteenth century to the beginning of the twentieth century. This type of vehicle propulsion was replaced by internal combustion engines. Since the 1970s, thanks to various engineers from all over the world, this drive has returned to favor, and by that time many compressed air vehicles had already been created [1].

The main problem in designing a compressed air vehicle is the low energy content of compressed air, which is 0.5 MJ / kg and 0.2 MJ / l [2]. For comparison, the energy density of gasoline is 46.4 MJ / kg and 34.2 MJ / l, LPG 46.4 MJ / kg and 26 MJ / kg, diesel oil 45.6 MJ / kg and 38.6 MJ / l [2, 3]. To compete with other types of drive, the key aspect of compressed air vehicles is to achieve the highest possible efficiency to maximize the use of the already small amount of energy in compressed air. The efficiency of pneumatic systems is low if they do not use any energy recovery methods or optimize compressed air consumption. The efficiency of pneumatic tools is in the range of 10-15% [4].

Yusop [5] dealt with optimizing compressed air consumption. The author gives some advice on how to reduce compressed air consumption: the piston should reach the end of the cylinder; inlet valves should be mounted on cylinders with as short pipes as possible and use short-stroke cylinders with appropriately selected mechanical adjustment instead of long-stroke cylinders.
One way to recover compressed gas consumption is to use a flexible tank that can be charged with air flowing from the actuator. This type of energy recuperation has been used in ankle and foot orthosis [6]. The authors used 25% less gas in their system than in the system without recuperation.

This type of recovery was also investigated by Cummins [7] et al. Scientists initially expanded the air in a small-bore pneumatic cylinder, then the air was injected into a flexible reservoir to finally be released into a large-bore pneumatic cylinder. Researchers boast of increasing air consumption efficiency by up to 72%.

Another possibility to increase the efficiency of compressed air consumption is to use a bypass valve. Yang [8] et al. compared the compressed air consumption of an actuator powered by a 5/3 valve with the compressed air consumption of a cylinder; when the actuator chambers were additionally connected by a 3/2 valve, which allowed air to flow from the chamber with a piston rod to the chamber without a piston rod. They concluded that the use of a bypass valve allows compressed air energy savings of 12% to 28% compared to a system without a bypass valve.

Szakacs [9] was involved in the construction of a block model of the pneumatic system of a pneumatic vehicle in the MATLAB program. The author assigned each block to physical equations that describe the behavior of the gas in particular parts of the system. After the simulation, it was possible to observe the course of the system parameters, which allows testing the consumption of compressed air at various settings.

2. Research description
The study investigated various ways of powering the actuator to use the compressed air stored in the tank more effectively. The reciprocating movement of the actuator was converted into the movement of the pneumatic vehicle.

The aim of the work was to determine the input parameters of the pneumatic system, which:
• ensure the maximum possible range of the vehicle at an average speed of at least 15 km / h and,
• ensure the maximum speed of covering a distance of 250 m.
A diagram of the vehicle's pneumatic system is shown in Figure 1.

![Diagram of the pneumatic system](image_url)

**Figure 1. Diagram of the pneumatic system.**

The study investigated the following ideas for the maximum use of energy stored in compressed air:
1. Partial power supply to the actuator. The goal is to make the actuator move through the expanding gas and not through the air flow.
2. Various values of gear ratios; the values of gear ratios directly depend on the values of the actuator resistances.
3. Minimizing pressure reduction on the reduction valve (1.2) in the pressure reservoir (1.1) – various values of the pressure supplying the actuator were tested.
4. Using buffer tanks (3.3) of different sizes – the tank should be large enough to be able to supply the actuator with air dynamically and collect heat from the environment to heat the air (the temperature of air has decreased after the reduction), but at the same time small enough so that the air does not expand unnecessarily in it.

The following ideas for maximizing vehicle speed were investigated in the study:
1. Deflating air before reaching dead center and simultaneously energizing the opposite chamber, this is to accelerate the piston travel through dead center.
2. Partial power supply of the actuator; this is aimed at a more efficient use of compressed air from the buffer tank (the air supply from the pressure tank is strongly limited by the reducer).
3. Using buffer tanks of different sizes, this is to store a large amount of compressed air downstream of the regulator, through which there is a small flow.

4. Gear shift time - This is to obtain a high torque output from the variator at the beginning of travel in order to overcome inertial resistance. As the vehicle speed increases, the variator will reduce the torque and increase the rotational speed on the transmission output shaft.

The designed circuit works as follows. Air from a 10-litre compressed air container (1.1) with a working pressure of 200 bar is reduced at the pressure reducing valve (1.2) to pressures ranging from 3 bar to 10 bar. Then the air flows through the safety stop circuit (2.1, 2.2, 2.3, 2.4, 2.5, 2.6, 2.7). Later, the air flows through the buffer tank (3.3) and other valves that enable its connection (3.1, 3.2, 3.4). The pressure regulator (4.2) then supplies air to the solenoid valve (5.2). Pressure regulator 4.2 is controlled by a pressure regulator (4.1), which is electrically controlled in proportion to the displacement of the accelerator pedal.

The solenoid valve (5.2) directs air to the right or left actuator chamber (5.5). When the piston moves to the right, air from the right chamber is released by valve (5.3), and in the event of left-hand movement of the actuator, air from the left chamber is discharged through the valve (5.3 (2)). The PLC controls the opening and closing of the valves. It operates based on information about the position of the piston from the position sensor (5.6). The pneumatic actuator drives the drive train, which transfers power to the wheels.

The controller is powered by two 12 V batteries connected in series. Data from pressure sensors (3.5, 5.4, 5.4 (2)) and from the piston position sensor (5.6) are transmitted through the controller and router to the computer, so that the pressure waveforms and the piston position can be analyzed for the correct efficiency of system operation.
In the Simcenter Amesim program, a block model was built containing all pneumatic and mechanical elements of the system, as well as control functions to be performed by a PLC controller.

The block model representing the pneumatic system is shown in Figure 2. Each block has boundary values such as pressure, flow rate coefficient, orifice area, etc.

Figure 2. Pneumatic block diagram (Simcenter Amesim).

3. Measurement results

3.1. Economic Driving
Measurements were carried out for five variants of the size of the supplied chamber: 10, 20, 40, 60 and 100%. For example, the variant of 10% power supply to the chamber consisted of feeding the chamber while the piston was 5 cm from its dead center (the stroke of the actuator is 50 cm). After exceeding 5 cm, the air supply was cut off. The further movement of the piston occurred due to the expansion of the gas.

In each variant, the vehicle parameters were tested for four pressure values (4, 6, 8, 10 bar) and four gear ratio values in the variator in the drive system (0.5, 1, 1.5, 1.9).

The diagrams show the range of the vehicle as a function of the setting of the reducing valve for different values of the gear ratio. There is a different graph for each air dose.
Figure 3. Range-pressure graph (the amount of air dose is 10%).

Figure 4. Range-pressure graph (the amount of air dose is 20%).

Figure 5. Range-pressure graph (the amount of air dose is 60%).
In most cases, the vehicle traveled further, with a lower dose of air supplied to the actuator; the higher the pressure setting was on the reduction valve, the lower was the gear ratio. It was noticed that the vehicle had the greatest range (8114 m) for the air dose of 10%, the setting of 10 bar on the reduction valve and for the smallest gear ratio (0.5 – maximum multiplication of gear rotational speed, maximum load on the piston rod). For this air supply variant, figure 7 shows a diagram showing the position of the piston and the pressure in the cylinder chambers as a function of time. In the chart, we can notice the delivery of a dose of compressed air to the chambers of the actuator and the next expansion which causes the piston to move.

For these parameters of the system, further studies were carried out to select the optimal size of a buffer tank. Vehicle range tests were carried out for 5 buffer tank sizes (0 l, 1 l, 5 l, 14 l, 24 l).
The test results are shown in diagram 8.

![Diagram showing influence of buffer tank size on vehicle range](image)

Figure 8. Influence of the size of the buffer tank on the range of the vehicle.

The diagram shows the range of the vehicle depending on the size of the buffer tank. The vehicle has traveled the longest distance for a 5-l tank (8667 m). The range was shorter with the use of tanks with a capacity of 1 l (8371 m), 14 l (8347 l), and 24 l (8263 m). Complete abandonment of the tank significantly reduces the range of the vehicle.

The size of the buffer tank has little effect on the efficiency of air consumption. However, it cannot be completely dispensed with, because then it is not possible to supply the actuator chamber with a dose of air at a pressure of 10 bar, even with an air dose of 10%. Consequently, the cylinder chambers are supplied with a lower pressure.

Figure 9 shows the maximum range of the vehicle obtained during the simulation and the pressure drop in the pressure tank (1.1 in Figure 1) as a function of time for the most optimal system parameters for economic driving.

![Graph showing range and pressure drop](image)

Figure 9. Graph of the greatest range and the pressure drop in the pressure tank as a function of time.
3.2. Driving fast
To maximize the vehicle speed and minimize the driving time of 250 meters, the following parameters were tested:

- the size of the air supply to the actuator chamber [%],
- early opening of the intake and drain valves before reaching the dead position [cm],
- gear shift time (from the variator gear ratio of 1.9 to the gear ratio of 0.5) [s],
- the size of the buffer tank [l].

The results in the form of graphs are shown in Figure 10.

![Graph of travel time of 250 m as a function of the size of the buffer tank for various amounts of air dose.](image)

Figure 10. Graph of the travel time of 250 m as a function of the size of the buffer tank for various amounts of air dose.

The travel time of 250 m is shorter, the larger the buffer tank. The travel time of the 250 m section decreases with decreasing the value of the air dose to 40% and then increases.

The pressure diagrams (figures 11 and 12) are shown to explain the different 250 m travel times for different air doses. They show the pressure in the cylinder chamber with the piston rod, the pressure in the cylinder chamber without the piston rod, and the pressure in the buffer tank as a function of time for two extreme values of air doses: 10% and 100%.

The graph in Figure 11 shows the pressure in the buffer tank and the pressure in the actuator chambers as a function of time for the air dose of 10%. After driving a distance of 250 m, the pressure in the buffer tank is approximately 6.5 bar (absolute pressure).
Figure 11. Graph of the pressure in the buffer tank and the pressure in the actuator chambers as a function of time for the air dose of 10%.

Figure 12. Graph of the pressure in the buffer tank and the pressure in the cylinder chambers as a function of time for the air dose of 100%.

The diagram in Figure 12 shows the pressure in the buffer tank and the pressure in the actuator chambers as a function of time for the air dose of 100%. After driving a distance of 250 m, the pressure in the buffer tank is approximately 2 bar (absolute pressure). This graph shows a more dynamic pressure
drop in the buffer tank compared to the variant of feeding the actuator with a 10% air dose. The pressure drop in the buffer tank results from the greater demand of the actuator for air than the flow through the pressure reducer (block 1.2 in Figure 1).

For the variant for which the vehicle traveled 250 meters in the shortest time, further optimization simulations were carried out. The effects of early valve opening and shifting timing on vehicle travel of 250 m were measured. The simulation results are shown in the diagram in Figure 13.

![Graph of the 250 m travel time as a function of earlier valve opening for different times gear overrides.](image)

The graph shows that the shorter the shift time was, the shorter was the travel time of 250 meters. This parameter is very important — between the travel time of 250 m for the gear shift time of 0 s, and the gear travel time of 8 s is a difference of more than 2.5 s. From this analysis it follows that the variator used in the vehicle is not needed. The actuator can generate a high torque on the drive wheel from the start of the vehicle motion.

The travel time of 250 m decreases with the increase of the earlier opening of the valves to the value of 2 cm, and after exceeding this value it increases.

Figure 14 shows the velocity and the greatest range of the vehicle as a function of time for the most optimal parameters of the pneumatic system for driving fast.
4. Summary

Thanks to the research, it was possible to indicate in which areas to look for optimal driving parameters (actuator operation). There are the following measures to minimize air consumption:

- Reduce the pressure drop on the reduction valve as much as possible - supply the actuator with doses of air at a pressure of 10 bar, which is the maximum pressure at which the pneumatic elements used in the system can operate,
- Adjust the energy of the air dose delivered to the actuator to the work so that the actuator will have to perform. This can be done by:
  - supplying brief air to the actuator chamber and then cutting off the air supply so that the piston moves as a result of air expansion,
  - appropriate selection of the gear ratio in the drive transmission system in such a way that the resistance on the piston rod is properly matched to the force generated by the expanding air,
- Select the pressure and amount of the air dose as well as the transmission ratio in the drive system in such a way that the piston is always able to move the entire stroke without stopping between dead centers,
- Select a buffer tank with a minimum capacity that will allow for dynamic supply of the actuator chamber with high pressure air.

There are the following measures to maximize vehicle speed:

- Use a buffer tank with a maximum capacity (during the dynamic supply of the actuator, the demand for air by the actuator is greater than it can flow through the reducing valve),
- Adjust the amount of air delivered to the actuator. It must be selected in such a way as to optimally use the air from the buffer tank. With a too high dose of air supplied to the actuator from the buffer tank, the air will be used very quickly and the air from the cylinder will not be able to flow through the reducing valve rapidly enough. This will result in feeding the actuator with low-pressure air doses. If the dose of air is too low, the air from the buffer tank will not be fully used and after driving a distance of 250 meters, the tank will still contain high-pressure air,
- Start deflating the air expansion chamber before the piston reaches its dead center and simultaneously start supplying the opposite actuator chamber. This allows the piston to reverse the direction quickly when it is in the dead center,
- Reduce the pressure drop on the reduction valve as much as possible – supply the actuator with doses of air at a pressure of 10 bar, which is the maximum pressure at which the pneumatic elements used in the system can operate,
- When the cylinder is used to carry a heavy load from the very beginning of its operation, the cylinder can generate a large force on the piston rod right away. The use of a variator to maximize torque has proved redundant in this case.

5. Conclusions
The article proposes the possibility of powering the actuator in such a way that the pneumatic vehicle has the greatest range and covers a distance of 250 meters in the shortest time. In both cases, the most important parameter turned out to be the amount of air delivered to the actuator.

In the case of economic driving, an equally important parameter turned out to be the value of the pressure reduction in the reduction valve. The gear ratio values, and the size of the buffer tank were also important, but to a lesser extent.

In the fast-driving variant, in addition to the amount of compressed air, the size of the buffer tank turned out to be of key importance. Gear shift time and the value of earlier opening of the drain and inlet valves had a lower influence on travel time.

It is worth mentioning that the simulation shows that there is no need to use a variator, because it is relatively easy to control the speed of the vehicle through the parameters of the pneumatic system, and the actuator can generate high torque on the drive wheel immediately in the run-up phase of the vehicle.

The simulations show a trend towards getting the longest range of the vehicle and the highest speed of the vehicle. The results are going to be compared with the experimental data while the vehicle is running.

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