University doctoral (PhD) dissertation theses

Energy Optimisation of Pneumatic Linear Drives by Positioning

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1. Background and objectives of the doctoral thesis

Energy optimisation is a fundamental question in numerous fields, such as in the field of movements and moving of objects. Linear movements comprise a significant part in the field of movements. There are numerous possibilities for realising a linear movement.

Due to their low price, the most widespread use is that of linear actuators, which can be classified as hydraulic, pneumatic, and electromechanical according to their corresponding mechanical principle. Comparing these three, there is a growing interest in pneumatic positioning. This is further motivated by the fact that pneumatic cylinders, being essential working parts, are widely used in the field of industrial automation thanks to their numerous advantages. The pistons of pneumatic cylinders are stopped in the two end positions in the case of traditional applications.

Pneumatic cylinders are simple, clean and trusty, they can work at high speed, their power-to-mass ratio is high, their maintenance is easy, furthermore, they are genuinely flexible, their explosion and fire safety is adequate, their operation is simple and their operational safety is good.

Pneumatic systems have evolved significantly in the last decades, which can be traced back to the intense development of the modelling of servo-pneumatic systems in the first place and to the application of the results of the theory of regulations in the second place. The positioning and trajectory tracking characteristics have been improved and the pneumatic actuators have become adequate for robot-technical purposes.

Objectives:

Per the above said, my research goals are the analysis of pneumatic linear drive systems, the broadening of their application and their energy optimisation by positioning. Considering the widespread use of pneumatic linear drive systems, a fruitful completion of my work would mean significant new results and an important step forward in the field of interest. One goal of my research is the creation of such an experimental device that is adequate for the execution of the needed measurements and experiments for our research under laboratory conditions.

During the research project, I shall design such a pneumatic, freely positioning drive system that will have a multiplied energy conversion efficiency. The energy optimisation of the drive and the creation of a new mathematic model are the key to the realisation of such a system.

2. Research Methods

Requirements for an experimental equipment:

- The equipment should be constructed from parts that are available on the commercial market;
- The equipment should fulfil any requirements that may come up during the research project;
- The equipment should be universal and easy to handle.

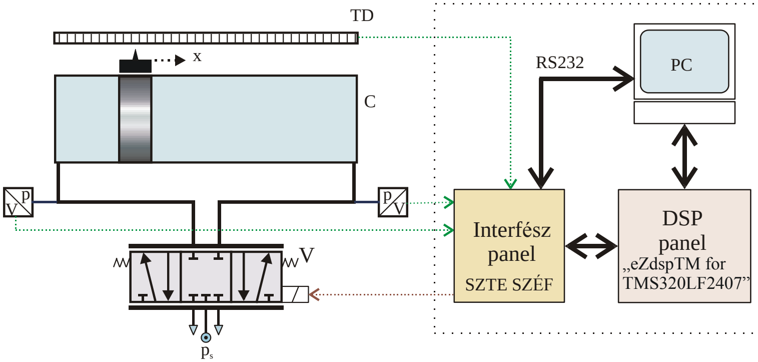

Fig. 1. Operating sketch of the experimental positioning equipment

Figure 1 shows the experimental equipment, its main part being a sliding cylinder of 32 mm diameter and of 500 mm stroke type MECMAN 170 (Rexroth RMC-BV), which is directed by a proportional valve type FESTO MPYE-5-1/8 HF-010B. The position of the piston is measured by an incremental position sensor type LINIMIK MSA 320. Speed and acceleration are calculated. The measurement of the pressure in the chambers is executed by a pressure sensor type Motorola MPX5999D.

3. Research Results

During my investigations, I have concentrated on the analysis of pneumatic drives. Their biggest advantage is their simple construction and their operational safety deriving from it. Consequently, an overcomplicated design is by no means desirable in the case of pneumatic drives if we want to achieve the above-mentioned goals.

The limits to the application of pneumatic drives are put by questions of braking and positioning. The aim of this work is to broaden the scope of efficiency in these questions, and especially to develop such drive systems that can adapt optimally to the tasks to be executed.

It is primarily while moving bigger masses and while working at a lower speed that the speed of a pneumatic cylinder cannot be adjusted precisely, the movement becomes difficult, different swings and vibrations occur. These swings cannot be avoided by adjusting the damping as usual.

Another problem while moving relatively big masses is the creation of big inertial forces in the end positions because of the short braking distance. This problem can be mitigated by reducing the operating speed, but this deteriorates the usability and the efficiency of the equipment.

A further disadvantage of pneumatic drives is the low efficiency, which derives from the speed control by damping and the unused expansion energy of the air.

The biggest problem is how to solve the positioning of the cylinders without a bumper. Many thinks that this problem cannot be solved because of the compression possibility of the air.

The basic connection shown in figure 2 ensures a high operating speed while delivering a safe braking, which makes it appropriate even under medium and high inertial pressure.

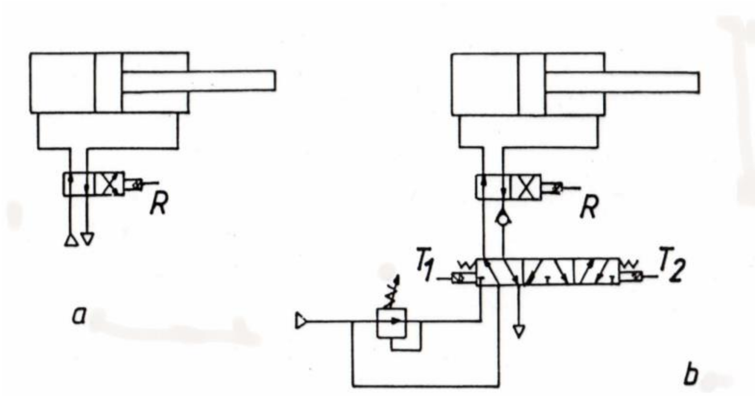

Fig. 2. Braking constructions

I have applied dimensionless mathematic models for the comparative analysis of the dynamic and energetic characteristics of the different constructional types:

$$\frac{d\sigma_1}{d_2} = \frac{K}{\gamma_{01}+\gamma}\left[A_1 Z_1 sign(\sigma_{M1} - \sigma_1)\varphi(I_1) - \sigma_1 \frac{d\gamma}{d\tau}\right] \qquad (1)$$

$$\frac{d\sigma_2}{d\tau} = \frac{K}{\gamma_{02}+1-\gamma}\left[A_2 Z_2 sign(\sigma_2 - \sigma_{M2})\frac{\varphi(I_2)}{\prod_{21}^{F}(\gamma_{02}+1-\gamma)} - \sigma_2 \frac{d\gamma}{d\tau}\right] \qquad (2)$$

$$\frac{d\theta_1}{d\tau} = \frac{\theta_1}{\sigma_1}\frac{d\sigma_1}{d\tau} + \frac{\theta_1}{\gamma_{01}+\gamma}\frac{d\gamma}{d\tau} - sign(\sigma_{M1} - \sigma_1)A_1 Z_1 \frac{\varphi(I_1)}{\gamma_{01}+\gamma} \qquad (3)$$

$$\frac{d\theta_2}{d\tau} = \frac{\theta_2}{\sigma_2}\frac{d\sigma_2}{d\tau} - \frac{\theta_2}{\gamma_{02}+1-\gamma}\frac{d\gamma}{d\tau} - sign(\sigma_2 - \sigma_{M2})\frac{A_2' Z_2 \varphi(I_2)}{\prod_{21}^{F}(\gamma_{02}+1-\gamma)} \qquad (4)$$

$$\frac{d\gamma}{d\tau} = \dot{\gamma} \qquad (5)$$

$$\frac{d\gamma}{d\tau} = B(\sigma_1 - \sigma_2 \prod_{21}^{F} - \chi) \quad (6)$$

$$\frac{dy}{d\tau} = \frac{\dot{\gamma}^2}{2B} \quad (7)$$

$$\frac{dM_s}{d\tau} = \bar{R} Z_1 \varphi(I_1) + R\left[Z_2 \varphi(I_2) \frac{1+sign(1-\sigma_2)}{1+|sign(1-\sigma_2)|} - Z_2 \varphi(I_2) \frac{1+sign(\sigma_2-1)}{1+|sign(\sigma_2-1)|}\right] \quad (8)$$

$$\frac{dM_s}{d\tau} = Z_1 T_1 \varphi(I_1) + T_2\left[Z_1 \varphi(I_1) \frac{1+sign(\sigma_K-\sigma_1)}{1+|sign(\sigma_K-\sigma_1)|} - Z_2 \varphi(I_2) \frac{1+sign(\sigma_2-1)}{1+|sign(\sigma_2-1)|}\right] \quad (9)$$

The results of the numeric integration of the equation system in the case of the basic structure with the values $\chi = 0{,}1$, $\gamma_{01} = \gamma_{02} = 0{,}15$, $\prod_{21}^{F} = 1$, $\sigma_a = 0{,}2$, $B = 0{,}1$ are demonstrated by figure 3, where σ, θ, γ, η, M_s correspond to the relative pressure, temperature, movement, time, values of the used air mass, χ is the indicator of the static load, φ(3),is the volume function, A and A' are modelling constants, B is the inertial indicator and Z the corrector evaluating the flow rate.

Figure 3 reveals that the connection ensures an even braking at a high operating speed. The relative mass of the compressed air used during one cycle is: M_s = 1.41. The above listed parameters correspond to an initially heavily loaded drive.

The energy efficiency ratio of a pneumatic drive is measured by the relative work ability, the biggest productive work that is executed by the unit mass of compressed air getting from the network to the drive.

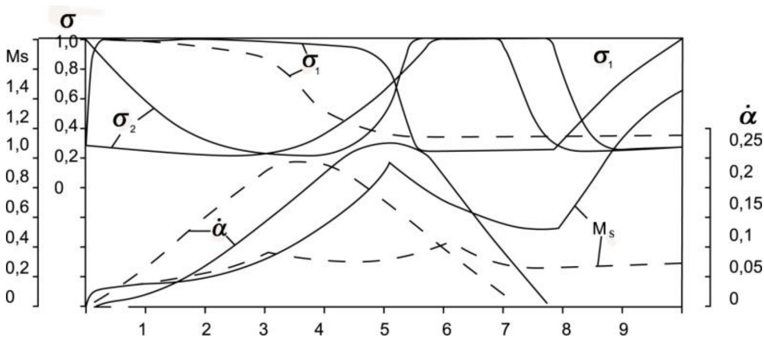

Fig. 3. The results of the numerical integration

It is possible to achieve a soft and no-beat stop with a proper controlling/direction of a classic drive system but the efficiency cannot be improved with this basic system (15-20%).

A substantial reduction of the unproductive energy consumption can only be achieved by creating a system that can adjust itself optimally to the different work phases of the drive.

I have determined by computer the transitional processes described by the equation-system (1-9) in the case of both drive types - the one with a traditional braking method and the other with the braking method developed by myself - under different static loading, and with different inertial indicators to determine the energy-efficient structures and the rational operational fields of pneumatic drives. The values obtained are shown in figure 4 (a, b, c, d).

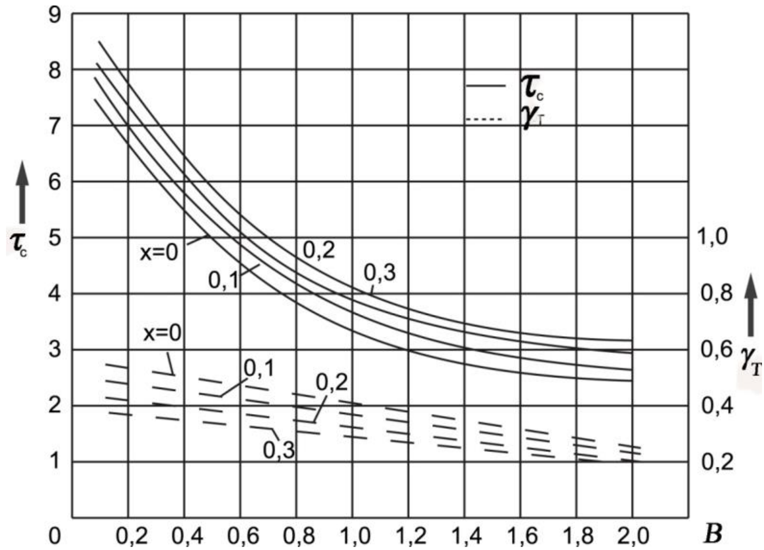

Fig. 4. a. Results of the computer analysis

The analysis of the above diagrams has shown that a construction per figure 2. ensures a higher operating speed in practically the whole field of investigation. The biggest energy saving appears at χ = 0-0.1. With the increase of χ the energy consumption of the drive with the modified connection can only be reduced at high inertial load (B = 0.1-0.5). At high static load χ > 0.3) and at low inertial load (B > 1.5) the application of the energy efficient structure is unsuitable.

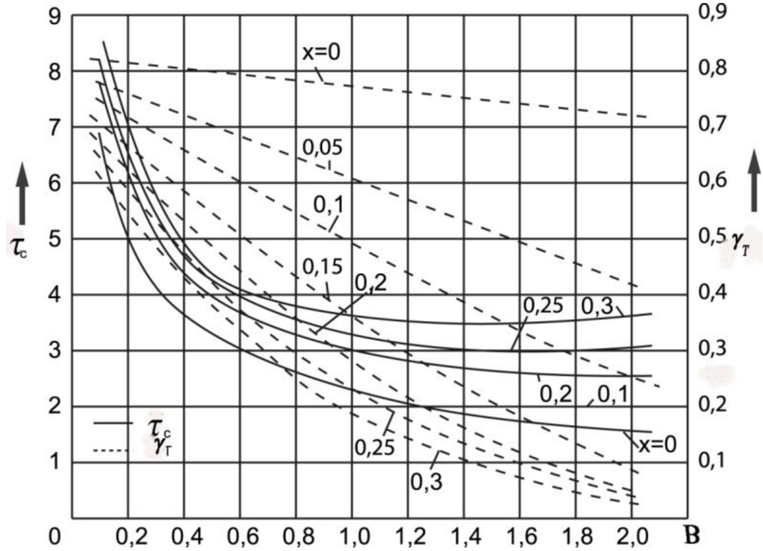

Fig. 4. b. Results of the computer analysis

Increasing B results in a speedier piston movement and in a shorter braking distance. Added to this, the damping wastage increases. For example, if $\chi = 0.1$, increasing B = 0.1 to B = 2 results in a similar twentyfold increase of the damping wastage, reaching one third of the total work ability of the compressed air (fig. 4. d).

At the same time, due to the shorter braking distance - being a consequence of the non-total expansion - the wastage ($\Delta\ E_{np}$) linked to it increases 3.7-fold. All this shows clearly that the energy efficiency decreases significantly at low inertial load.

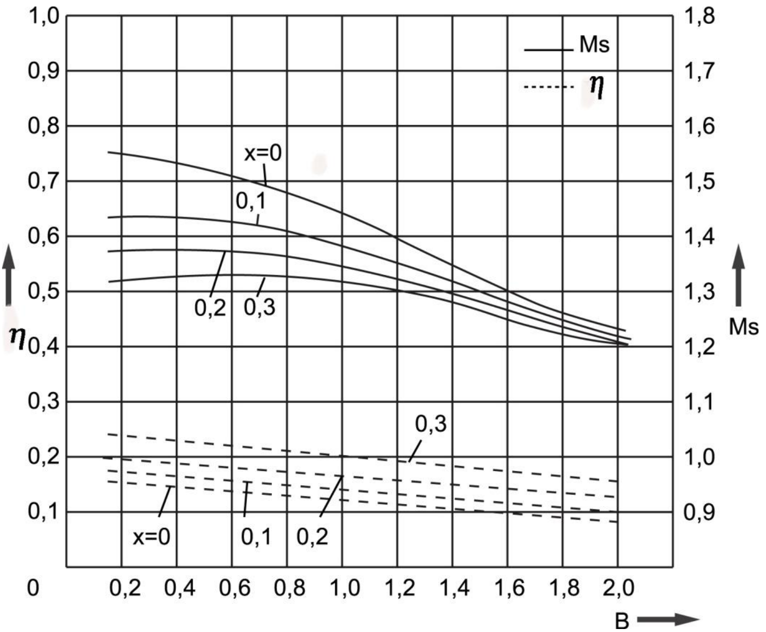

Fig. 4. c. Results of the computer analysis

Taking into account the raising prices of energy and the lowering prices of pneumatic equipment, the use of energy-efficient systems becomes more and more economic in practical.

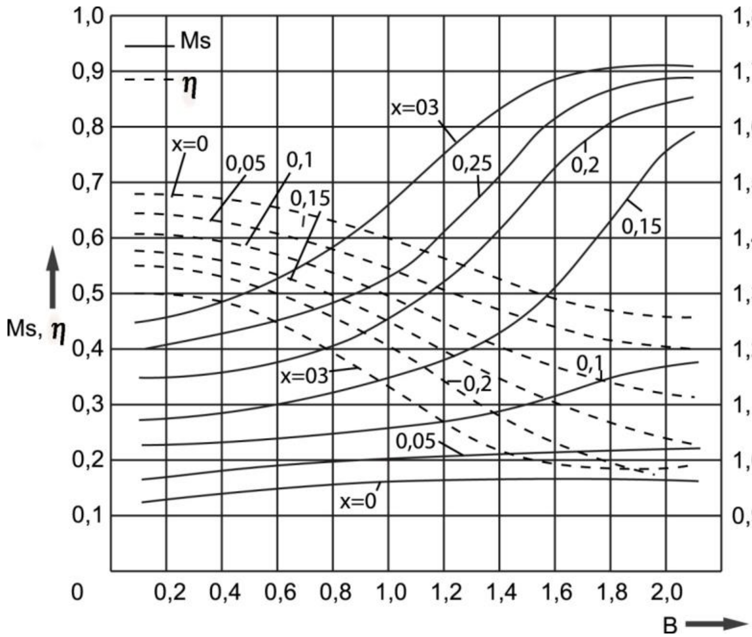

Fig. 4. d. Results of the computer analysis

Figure 5 shows a sketch of the freely positioning pneumatic drive developed by myself, which uses the previously described braking system. The module is stabilised in the desired position by a fixing. It can correct the positioning errors that occur due to the flexibility of air, the power supply pressure and the changing load with the help of the position sensing so that it is able to refine the optimal braking distance, to put it figuratively, the system becomes "autodidact".

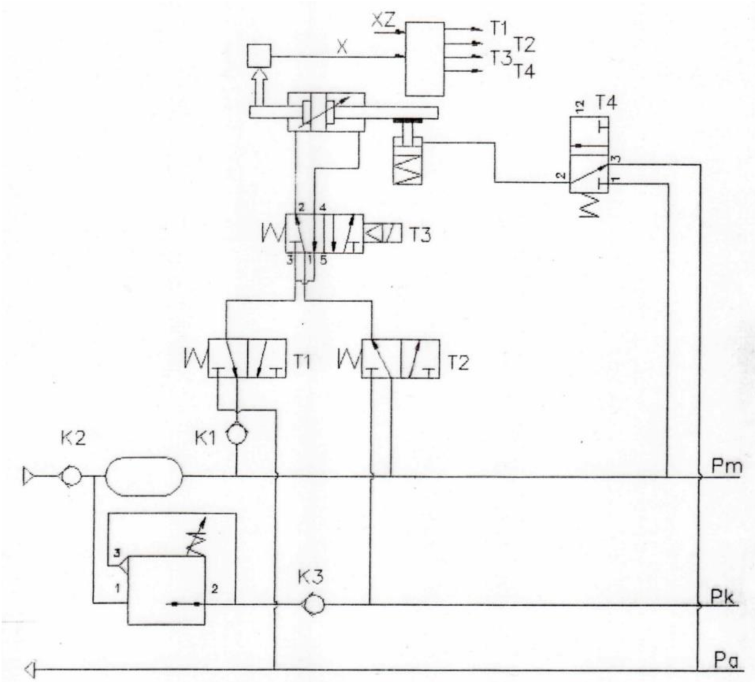

Fig. 5. Sketch of the developed freely positioning drive

4. New Scientific Results

1. I have designed and realised a new operating structure for the investigation of energy optimisation of linear drives (fig. 5), furthermore I have improved the previously used mathematic model:

$$\frac{dM_s}{d\tau} = \bar{R}Z_1\varphi(I_1) + R\left[Z_2\varphi(I_2)\frac{1 + sign(1-\sigma_2)}{1 + |sign(1-\sigma_2)|} - Z_2\varphi(I_2)\frac{1 + sign(\sigma_2 - 1)}{1 + |sign(\sigma_2 - 1)|}\right]$$

$$\frac{dM_s}{d\tau} = Z_1 T_1 \varphi(I_1) + T_2 \left[Z_1 \varphi(I_1) \frac{1 + sign(\sigma_K - \sigma_1)}{1 + |sign(\sigma_K - \sigma_1)|} - Z_2 \varphi(I_2) \frac{1 + sign(\sigma_2 - 1)}{1 + |sign(\sigma_2 - 1)|} \right]$$

2. I have concluded that it is possible to achieve a soft, no-beat stop with a classical linear drive system, given that it is properly controlled nevertheless it is not possible to improve the energy efficiency with this basic structure.

3. I have verified with experimental measurements that only 21.8% of the unit energy introduced into a traditional drive system is used, while in the case of the model developed by myself 59.5% of the unit energy introduced is used. This means a greater than 2.5-fold increase of used energy, which is verified by practical measurements.

4. The theoretical increase of used energy could be even 3 or 4-fold (up to 85-90%) but in practice the resonance of the cylinders limits the energy efficiency to 60%.

5. I have stated, based on the conclusions deriving from the analysis of figure 4. d, that the energy efficiency of the investigated pneumatic system (fig. 5) can be hold between 60-80% - instead of the 15-20% experienced in practice - if the inertial load (value B) is increased drastically, nearly doubled, and if the positioning system recommended by me is applied.

5. Practical applicability of the results

In my thesis, energy issues for pneumatic linear drives are analysed. For the practice results were born to increase the efficiency of drives, with respect to energy consumption reduction. Given that the pneumatic linear drives are becoming more widely applied on the fields of food processing, machine tool control, vehicle industry, many areas of robotics, the application of the my developed energy-efficient, affordable efficiency drives are a multitude of advantages for the user.

The new drive systems developed below, defined the optimum parameters can be offered to users:

1. Drive systems development was carried out, which manage the restrict factors of the use of energy-efficient linear actuators, mitigated the adverse effects occurring here. The planned drive systems optimally adapted to the specific tasks.

2. I planned simple braking systems, usable for daily practice. These braking systems in addition to reliable braking, high operating speed provided so that under widely applied to medium and large inertial loads.

3. Counter-current braking system is planned, in which the braking realized with the side of expansion in emerging overfilling and overpressure using realized. Systems performing such theses are useful for a continuous alternating motion. The braking energy

accumulated in a high percentage can be used for movement in the opposite direction starts. Such systems require power from the network only after the expansion, therefore significant energy saving can be realized.

4. For users who require a higher technical level I created a complex solution where you can control the braking pressure level and the capture with reduced pressure is feasible. This will reduce the energy need of fixing, it is feasible to counter-current braking and also constant differential pressure decelerates as well. It is therefore widely used as an alternative of conventional air movements with significantly less power consumption.

5. Low pressure positioning was planning a further opportunity to achieve energy and improve the positioning of pneumatic systems. With this system should significantly increase the system "intelligence" so the continuous process of drive parameters needed. They can determine the necessary pressure conditions based on iteration and only to overtake the load the minimum necessary energy applied into the system and take advantage of the expansion work. In arrival position at the end of braking, system uses mechanical fixing brake so at lower accuracy requirements the system can be considered as a freely position able system.

6. I developed an adjustable buffer positioning system that is a transition between energy saving and positioning. Specified by counter-current braking, therefore gives a much better efficiency

than conventional systems, but using the opportunity to achieve intermediate positions with application of switched stops or bumper. The end position damping is acted by dampening cylinders integrated into the bumper system. Such a system should achieve to secure the load in any position and are excellent for intermediate fixed positions. In this case, the positioning accuracy can be very large, only limited by the mechanical implementation.

7. I developed a freely position able, energy-saving pneumatic drive system that uses the above-described braking system during operation. The module is fixed to the desired position by stabilization of fixing brake. This improved drive system allows the analysis of pressure conditions and dynamic characteristics.

6. Bibliographie

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List of publications related to the dissertation

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